Title: Coherent Gravitational Waveforms and Memory from Cosmic String Loops

Speakers: Josu Calvo-Aurrekoetxea

Series: Strong Gravity

Date: January 21, 2021 - 1:00 PM

URL: http://pirsa.org/21010016

Abstract: We construct, for the first time, the time-domain gravitational-wave strain waveform from the collapse of a strongly gravitating Abelian Higgs cosmic string loop in full general relativity. We show that the strain exhibits a large memory effect during merger, ending with a burst and characteristic ringdown as a black hole is formed. Furthermore, we investigate the waveform and energy emitted as a function of width, radius and string tension GÎ¼. We find that the mass normalized gravitational-wave energy displays a strong dependence on the inverse of the string tension E_GW / M_0 âˆ• 1/GÎ¼, with E_GW / M_0 âˆ¼ O(1)% at the percent level, for the regime where GÎ¼ ~ 1e-3 . Conversely, we show that the efficiency is only weakly dependent on the initial string width and initial string radii. Using these results, we argue that gravitational wave production is dominated by kinematical instead of geometrical considerations.

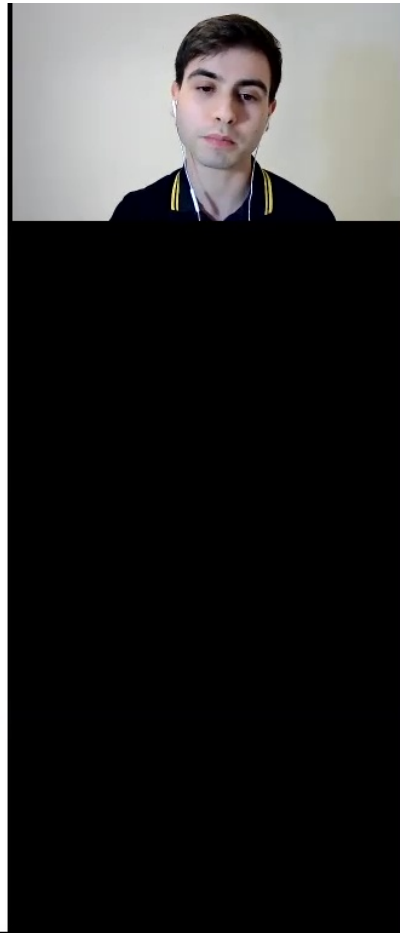
Coherent GW Waveforms and Memory from Cosmic String Loops

Josu C. Aurrekoetxea

@ Perimeter Institute (via zoom)

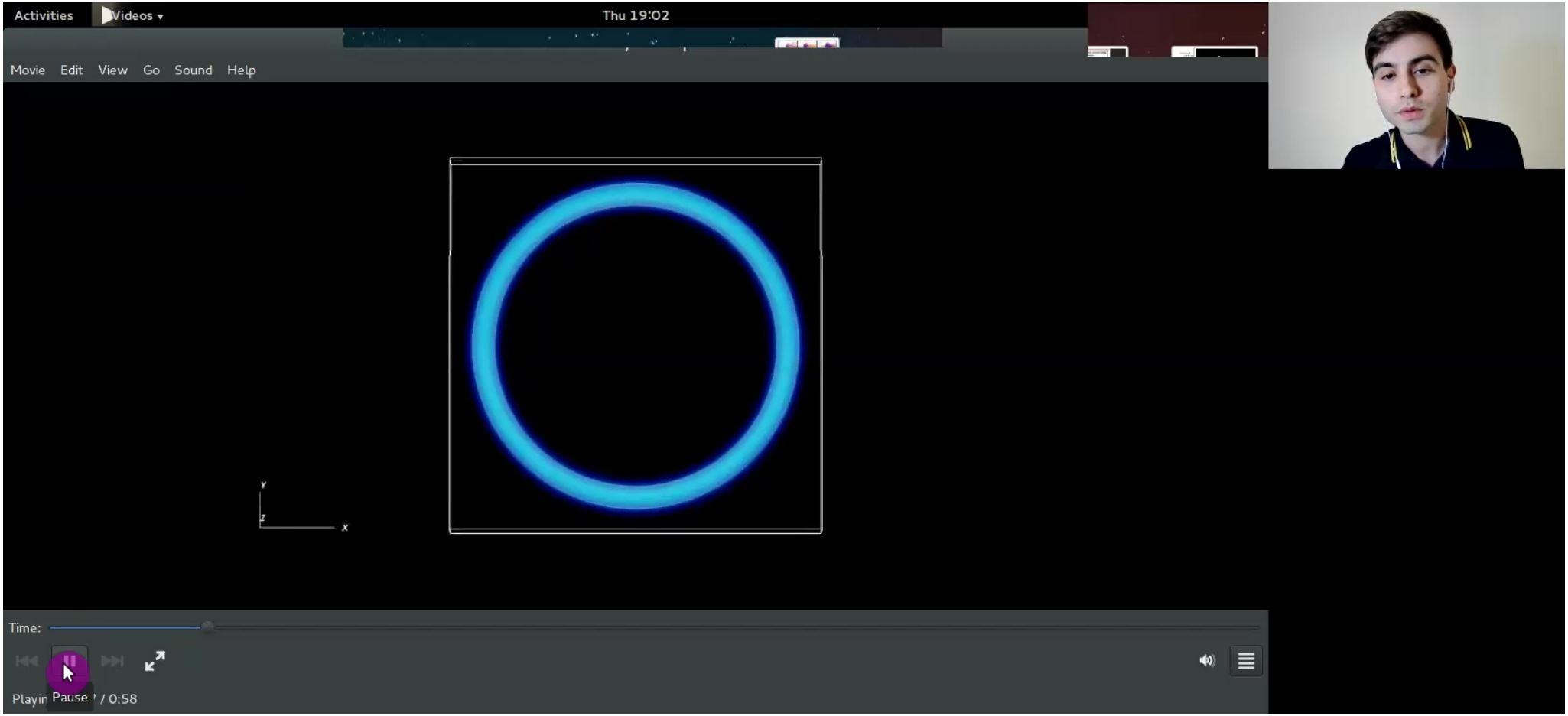
w/ Thomas Helfer & Eugene Lim

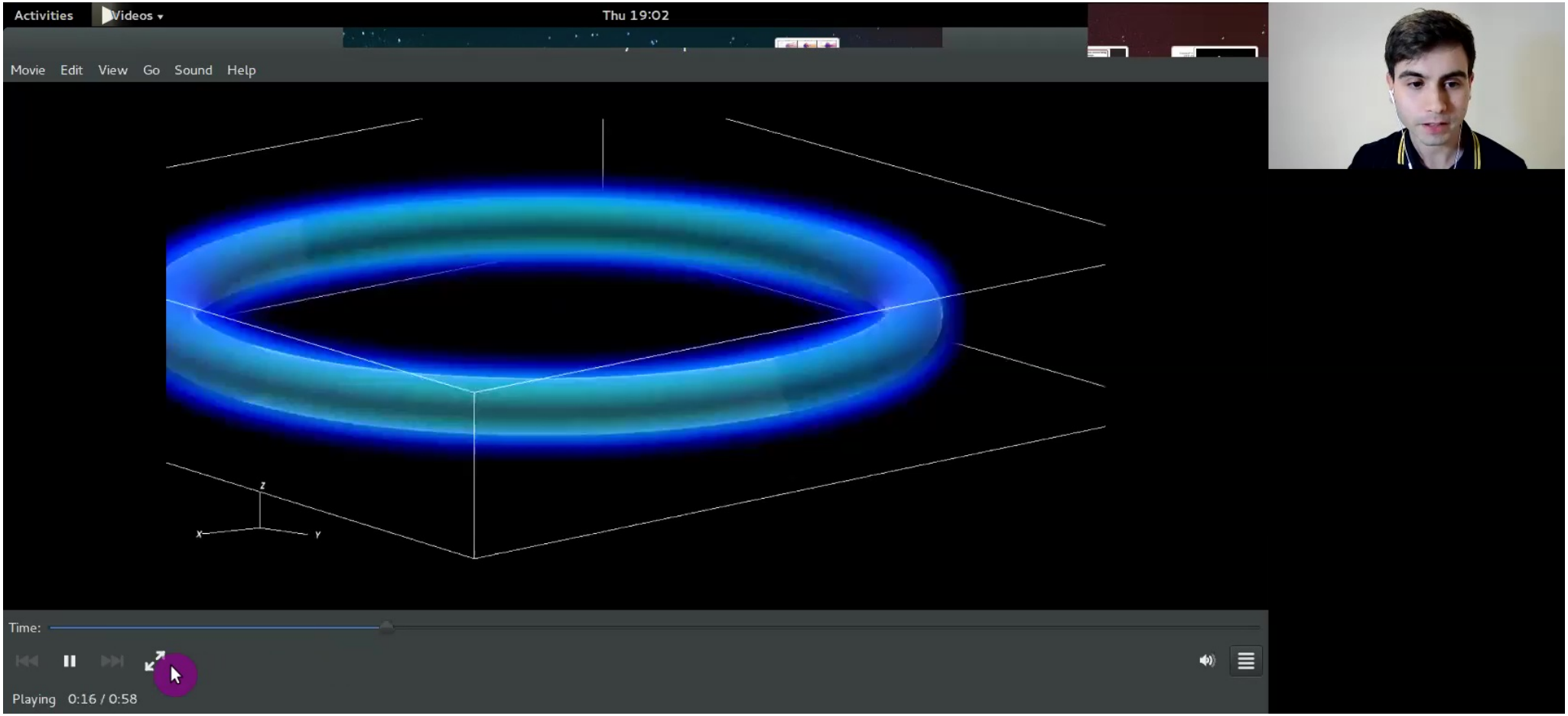
1808.06678
2002.05177

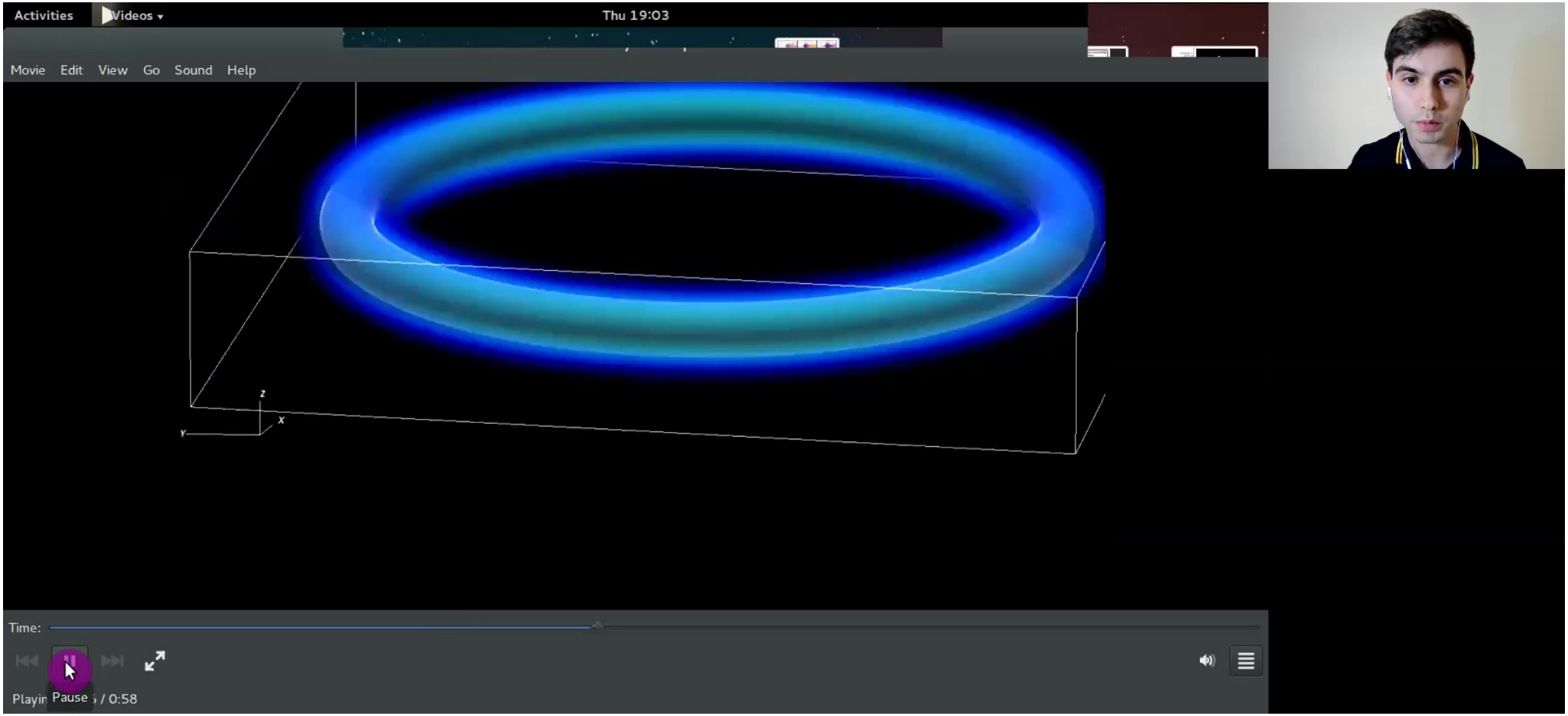


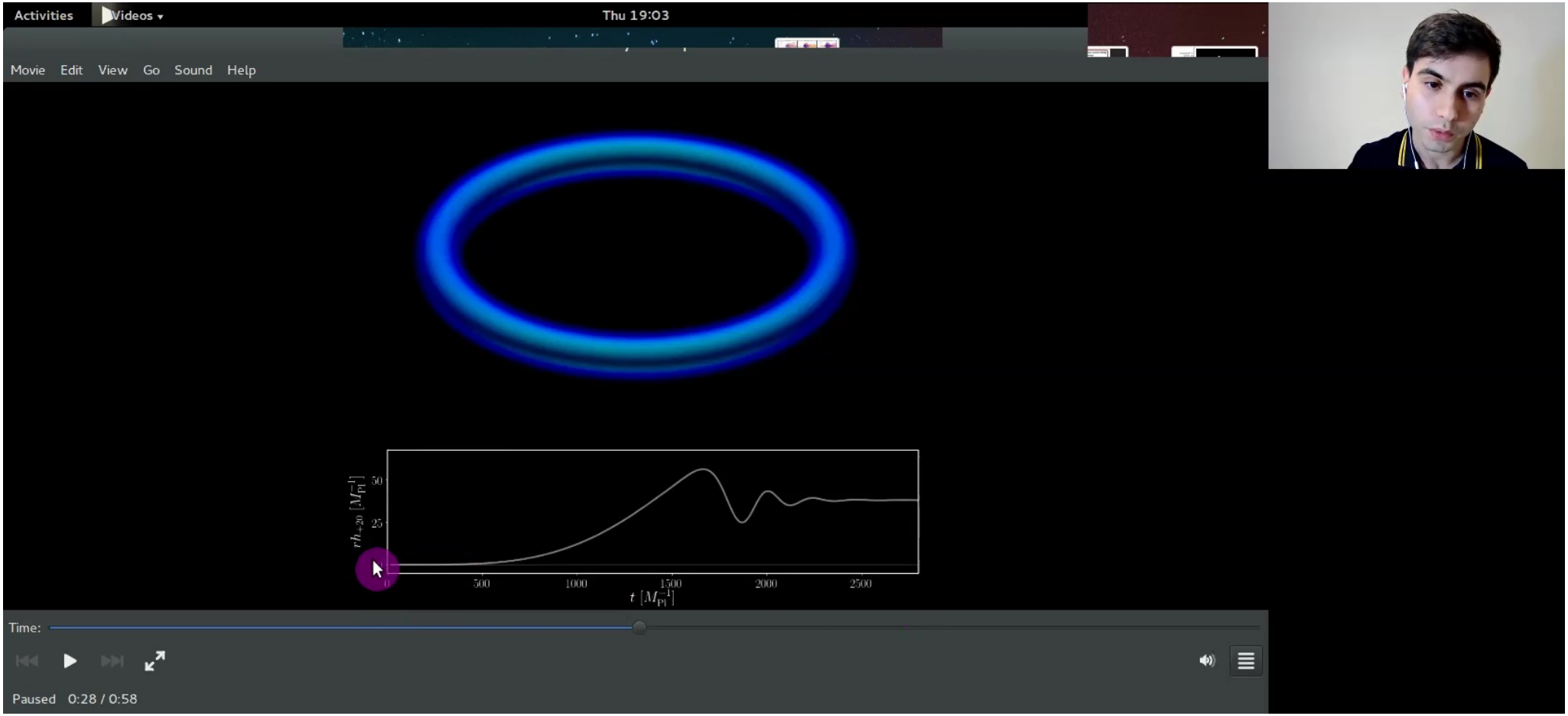
What is this talk about?

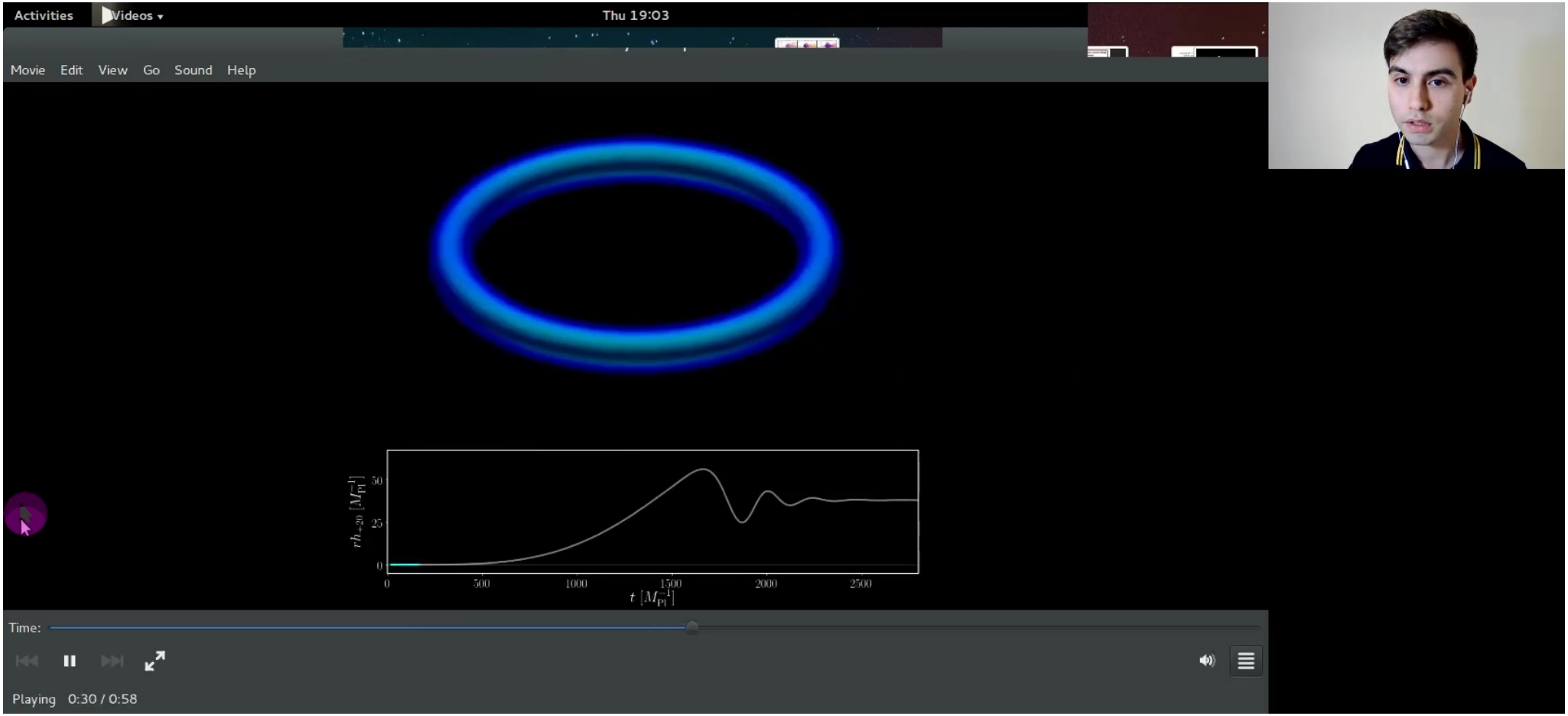
Movie

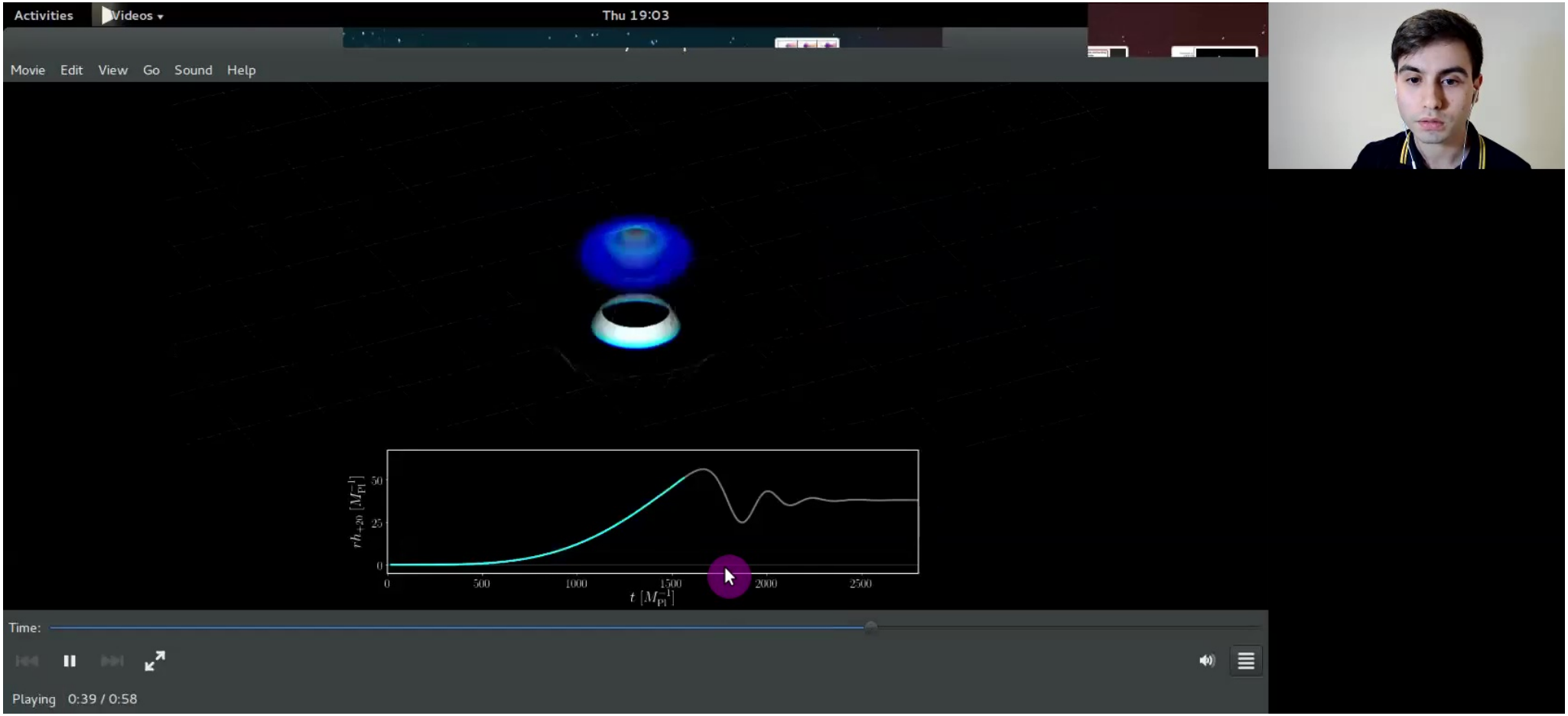

Activities
Videos
Thu 19:02
Movie Edit View Go Sound Help
Time:
Pause
/ 0:58

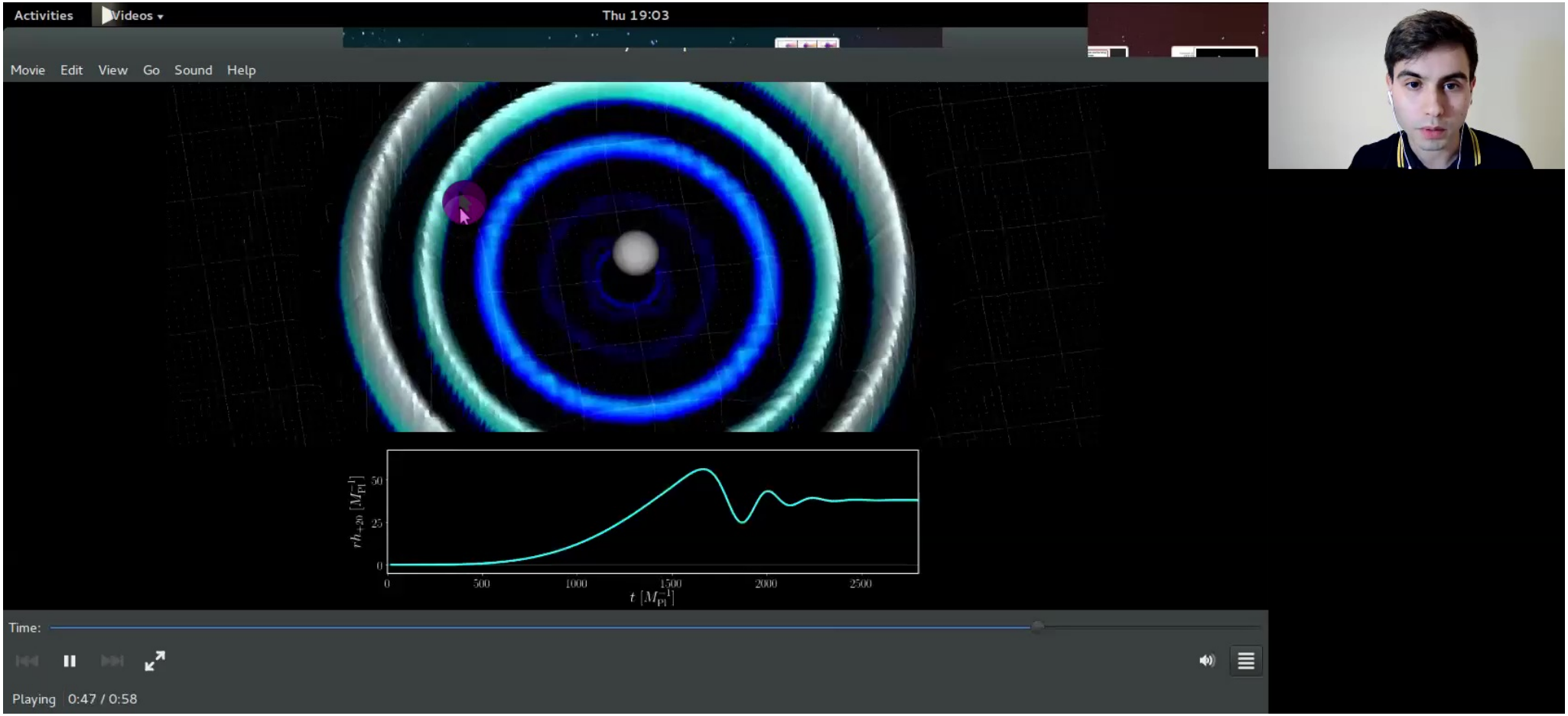

Activities
Videos
Thu 19:02
Movie Edit View Go Sound Help
z
x
y
Time:
Playing 0:16 / 0:58


Activities
Videos
Thu 19:03
Movie Edit View Go Sound Help
z
x
y
Time:
Pause
0:58


Activities
Videos
Thu 19:03
Movie Edit View Go Sound Help
$rh_{+20}\ [M_{\rm Pl}^{-1}]$
50
25
0
500
1000
1500
2000
2500
$t\ [M_{\rm Pl}^{-1}]$
Time:
Paused 0:28 / 0:58


Activities
Videos
Thu 19:03
Movie Edit View Go Sound Help
rh_{+20} $[M_{\rm Pl}^{-1}]$
50
25
0
0
500
1000
1500
2000
2500
t $[M_{\rm Pl}^{-1}]$
Time:
Playing 0:30 / 0:58


Activities
Videos
Thu 19:03
Movie Edit View Go Sound Help
$rh_{r=20}$ $[M_{\rm Pl}^{-1}]$
30
25
0
0
500
1000
1500
2000
2500
t $[M_{\rm Pl}^{-1}]$
Time:
Playing 0:39 / 0:58


Activities
Videos
Thu 19:03
Movie Edit View Go Sound Help
rh_{+20} $[M_{\rm Pl}^{-1}]$
50
25
0
0
500
1000
1500
2000
2500
t $[M_{\rm Pl}^{-1}]$
Time:
Playing 0:47 / 0:58

What are cosmic strings?

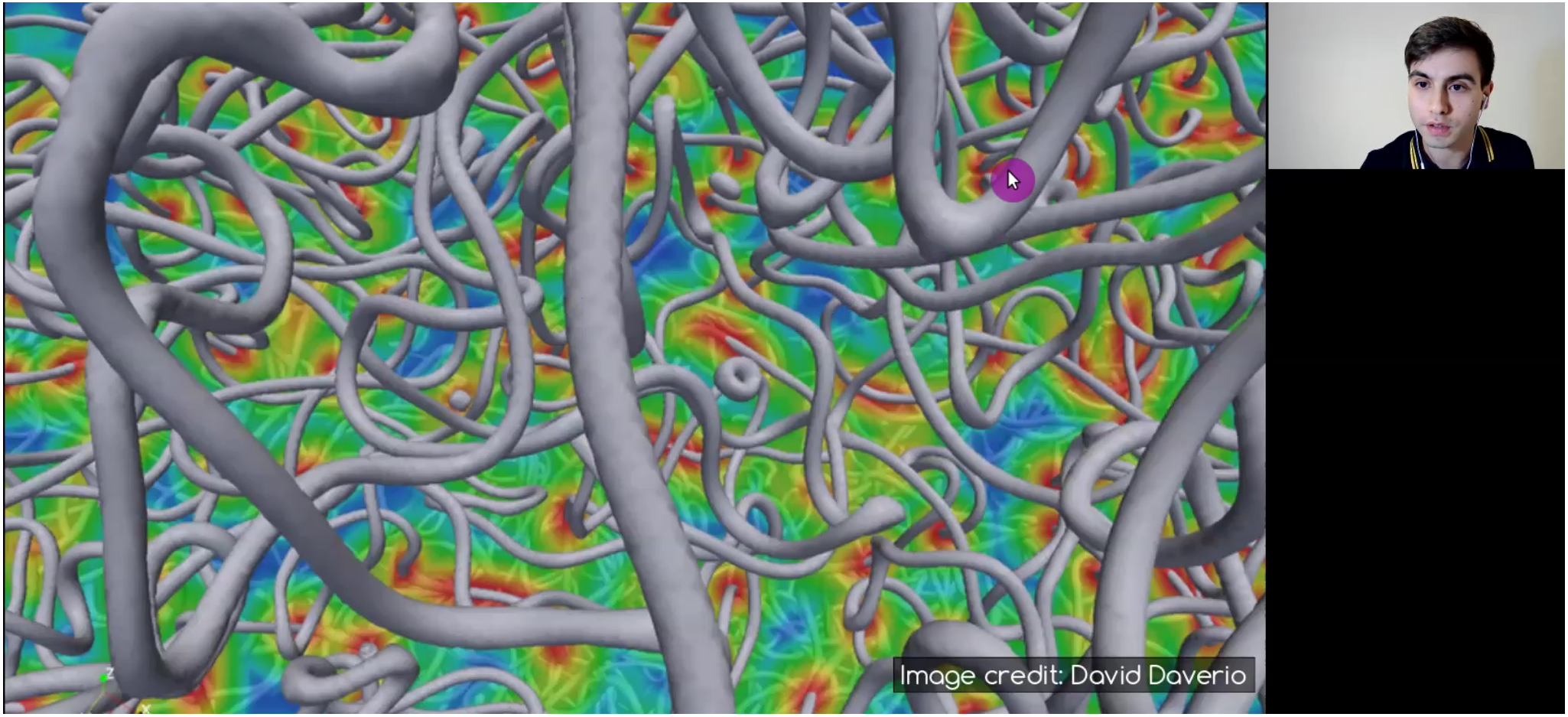
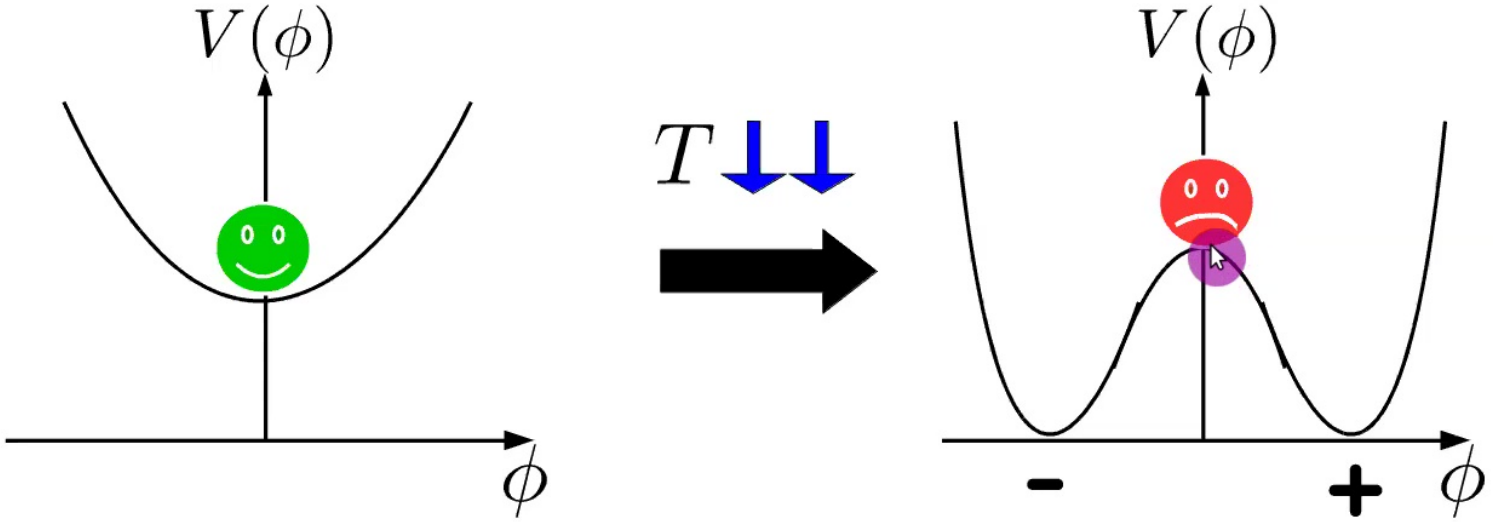
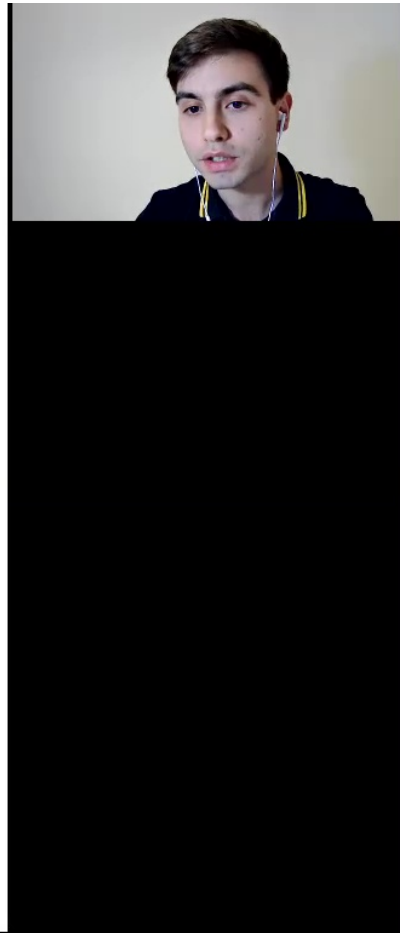


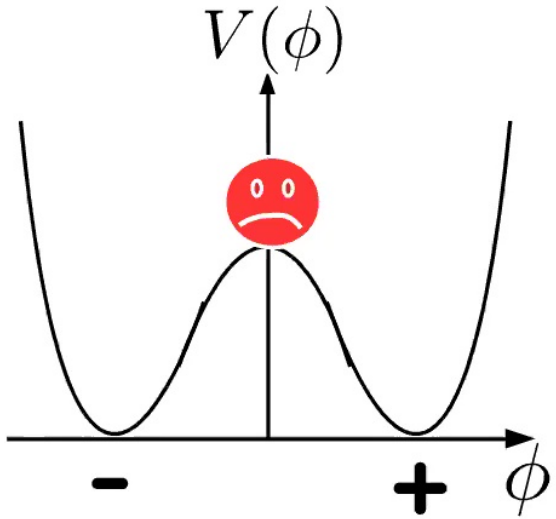
Image credit: David Daverio

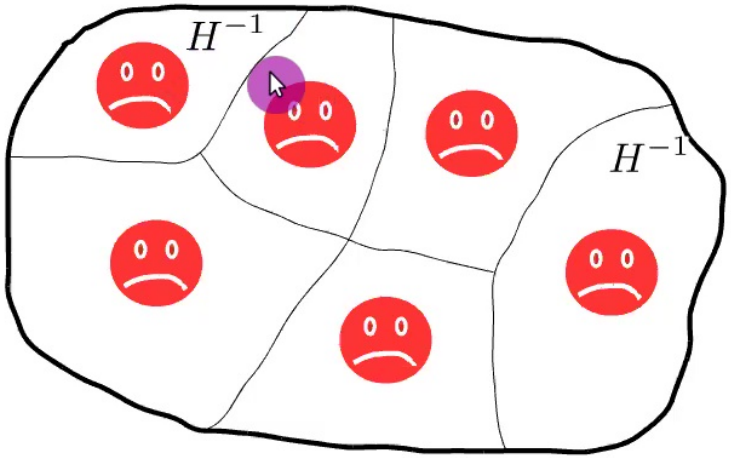
Domain Walls (2d)



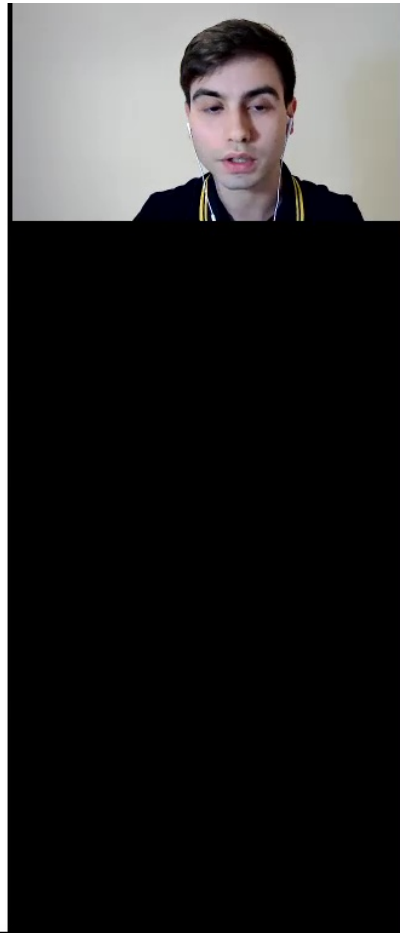


Domain Walls (2d)

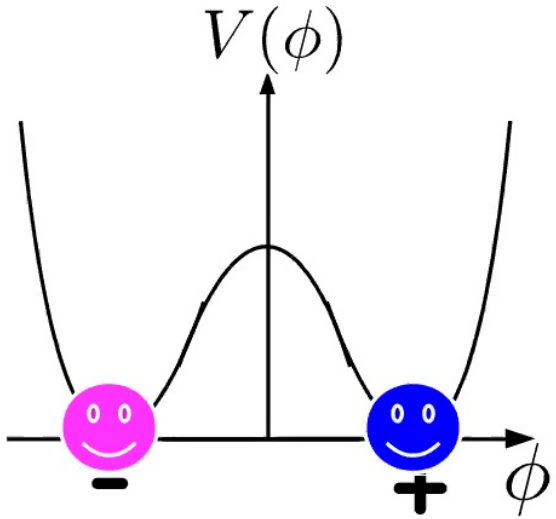


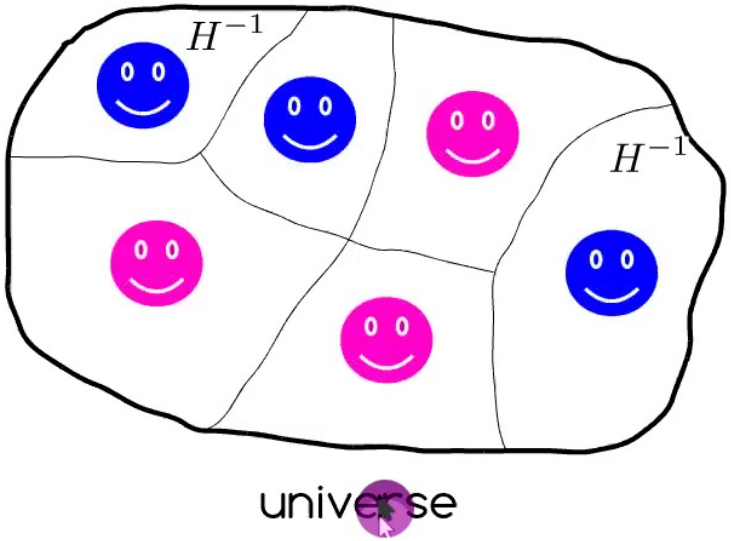


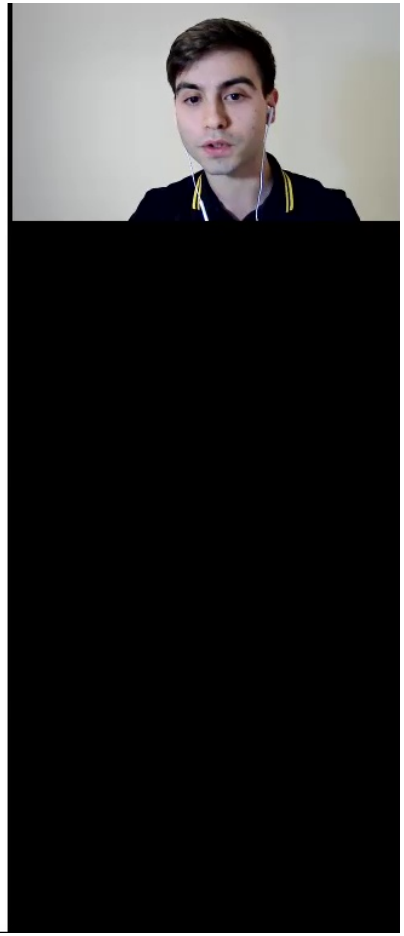
universe



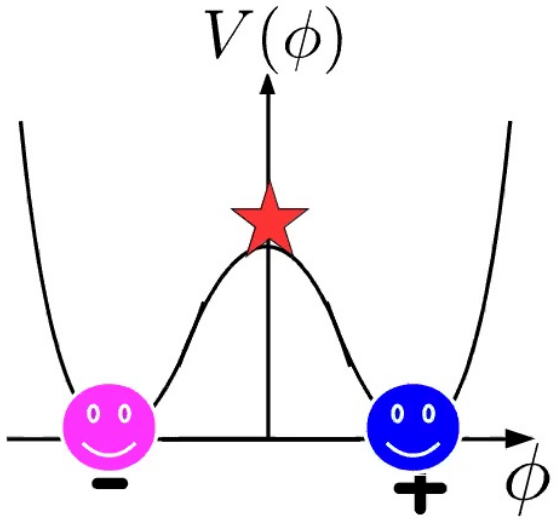
Domain Walls (2d)

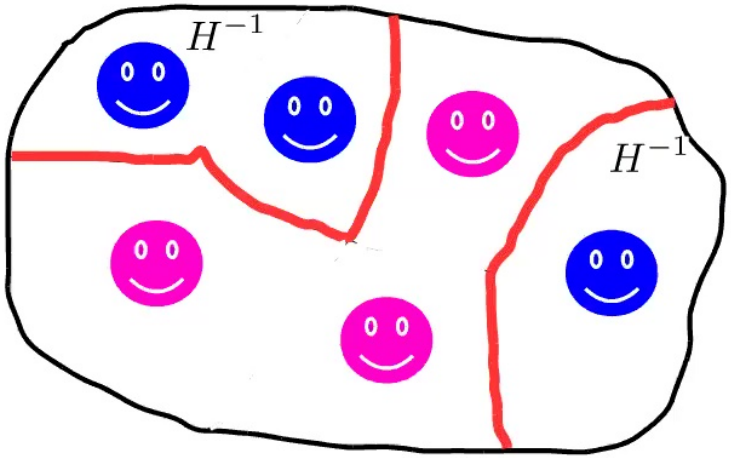






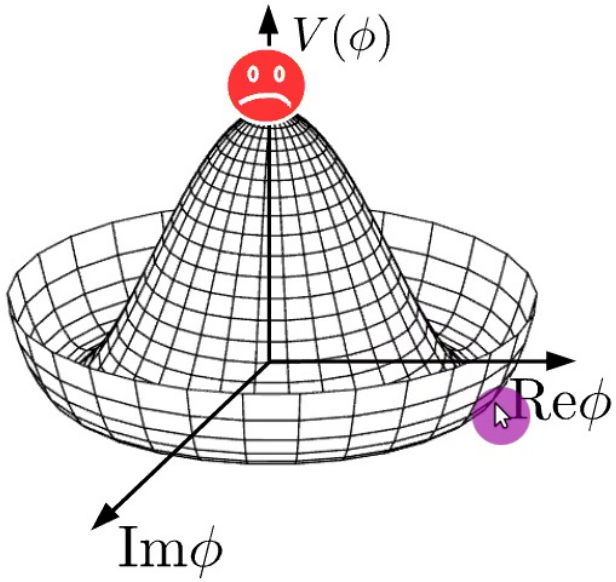
Domain Walls (2d)

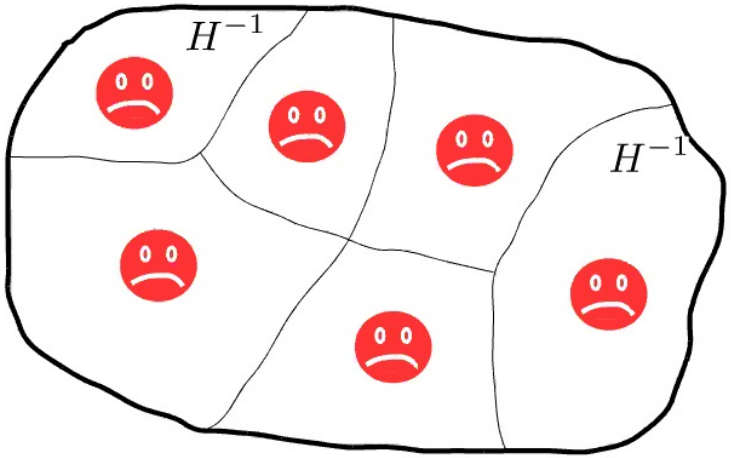




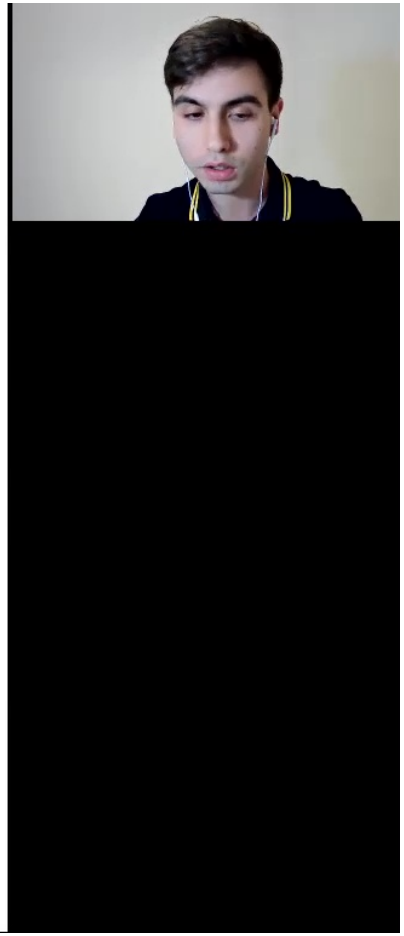
universe

Cosmic Strings (1d)

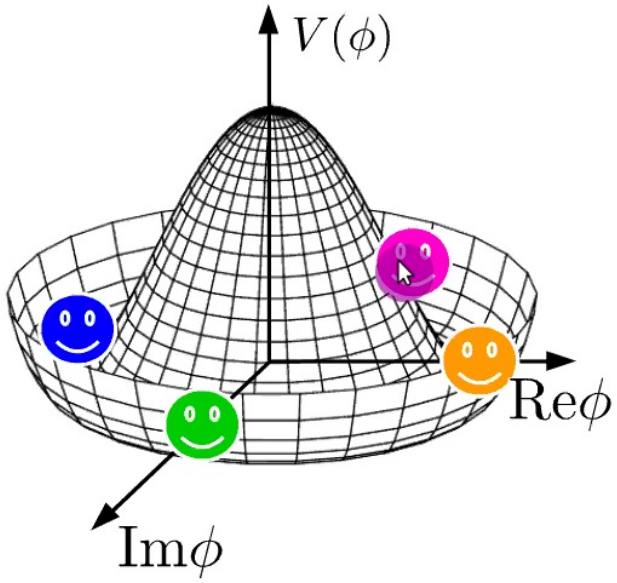


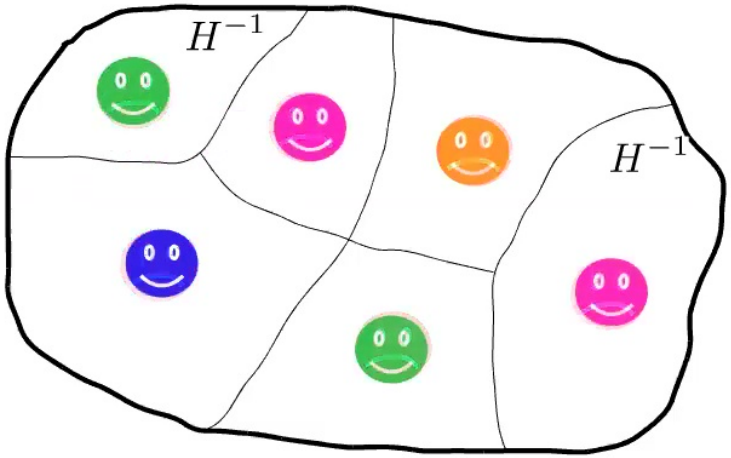


universe

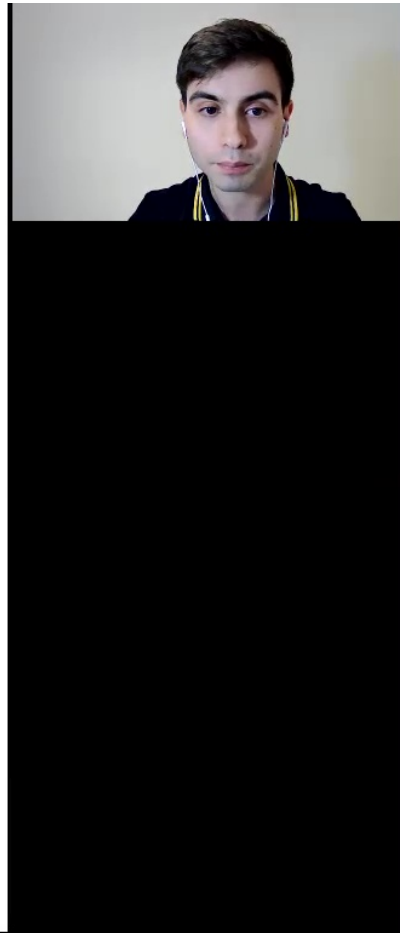


Cosmic Strings (1d)

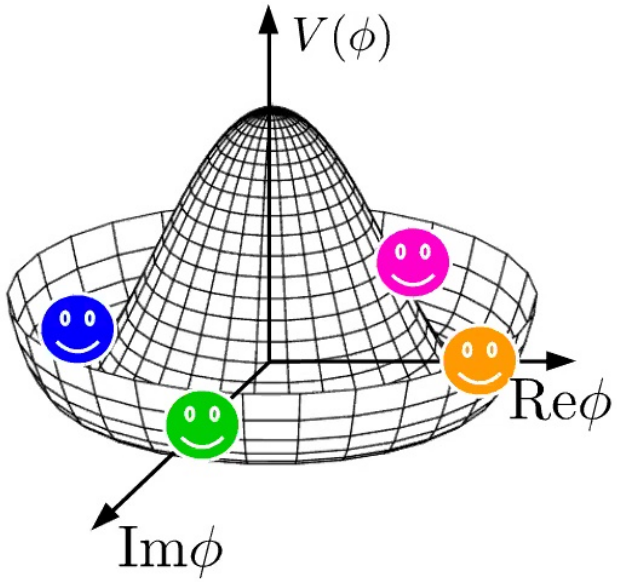


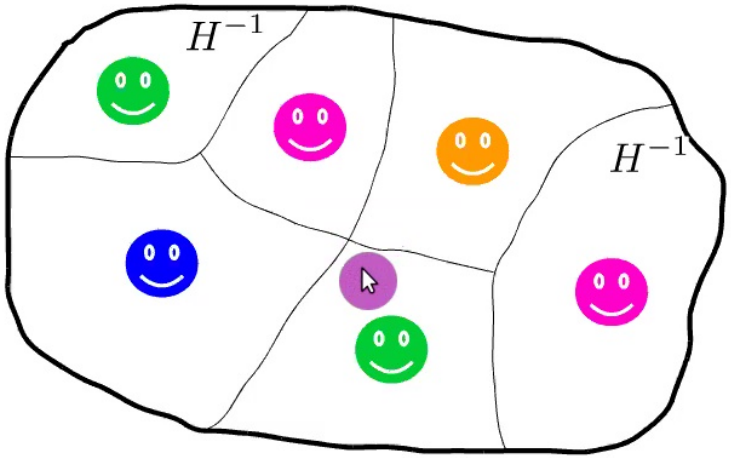


universe

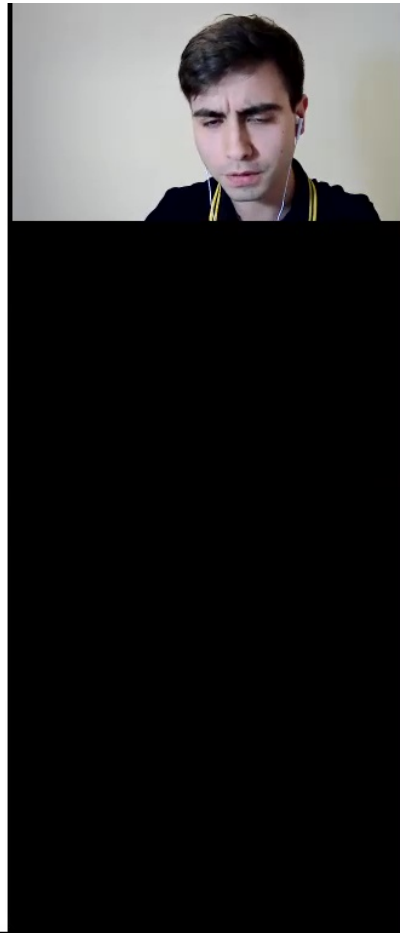


Cosmic Strings (1d)

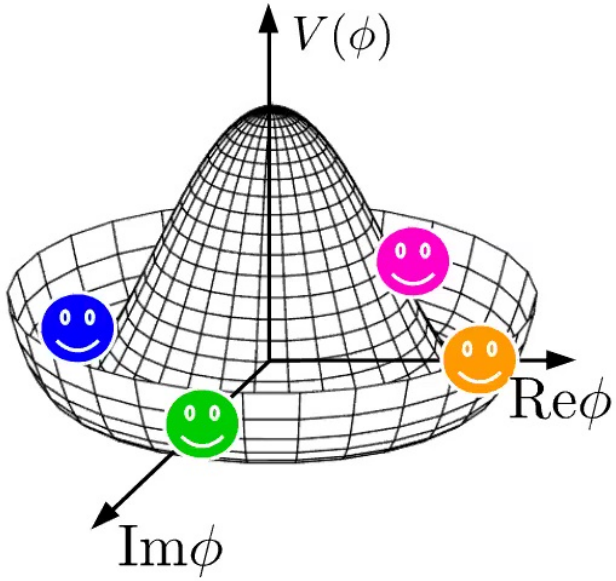


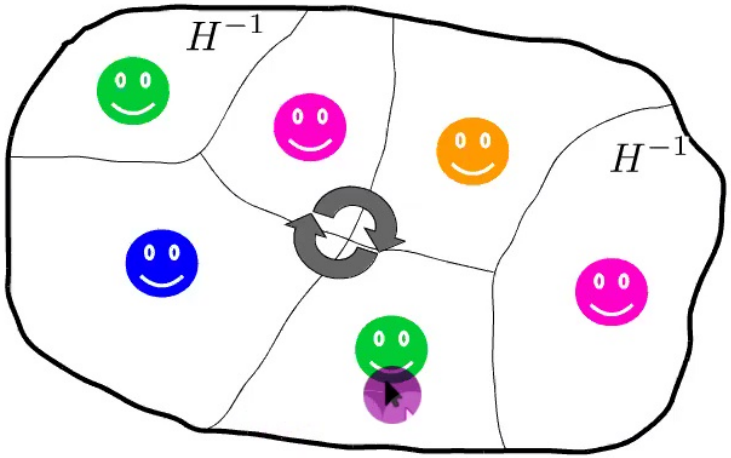


universe

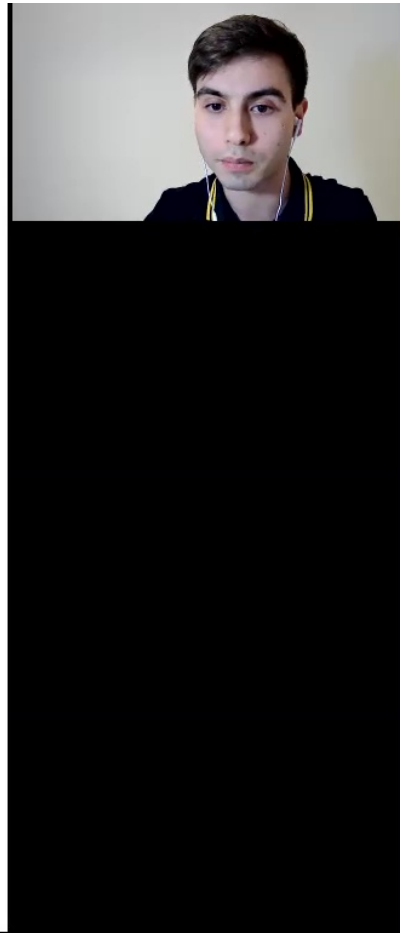


Cosmic Strings (1d)

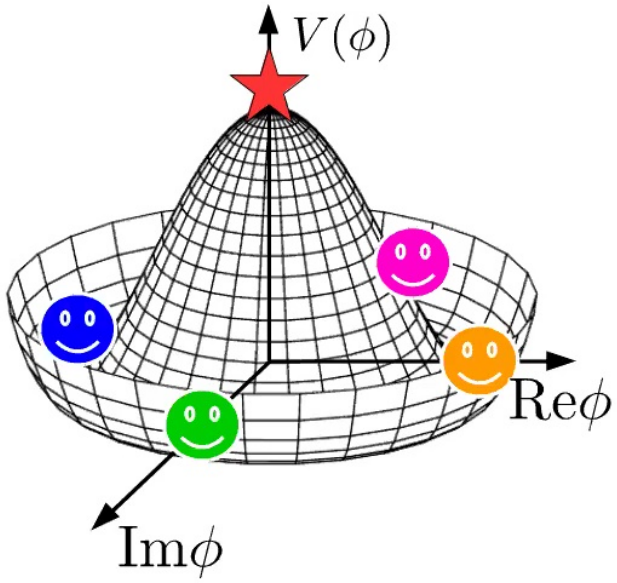


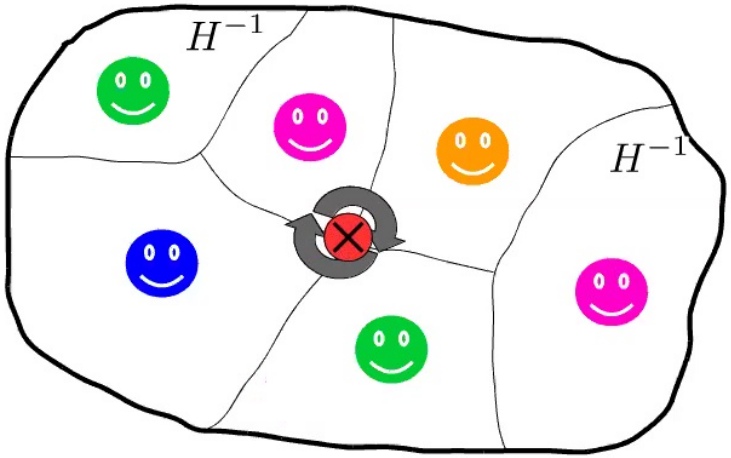


universe

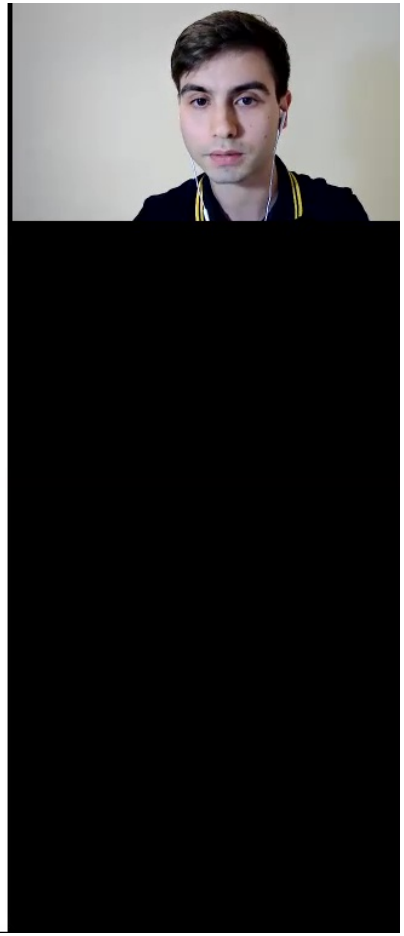


Cosmic Strings (1d)

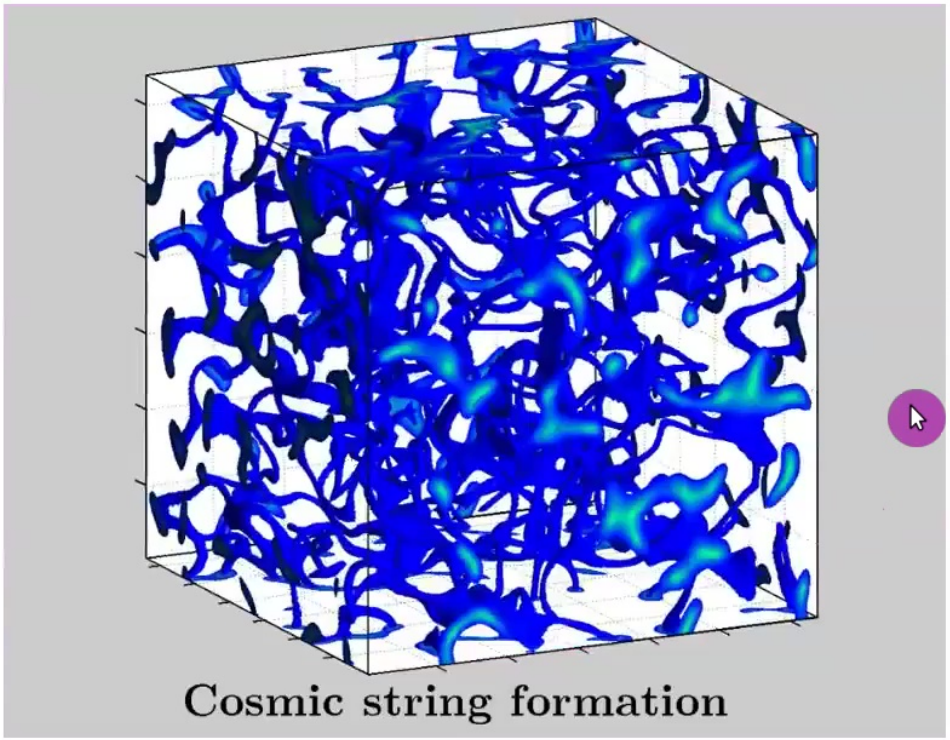




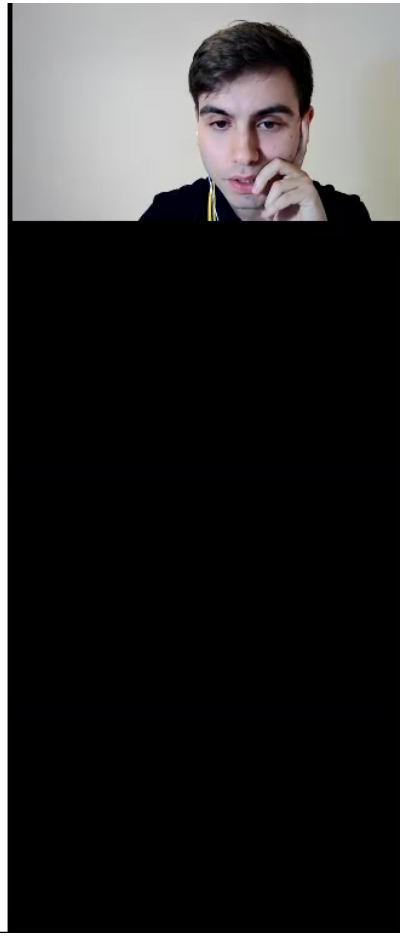
universe



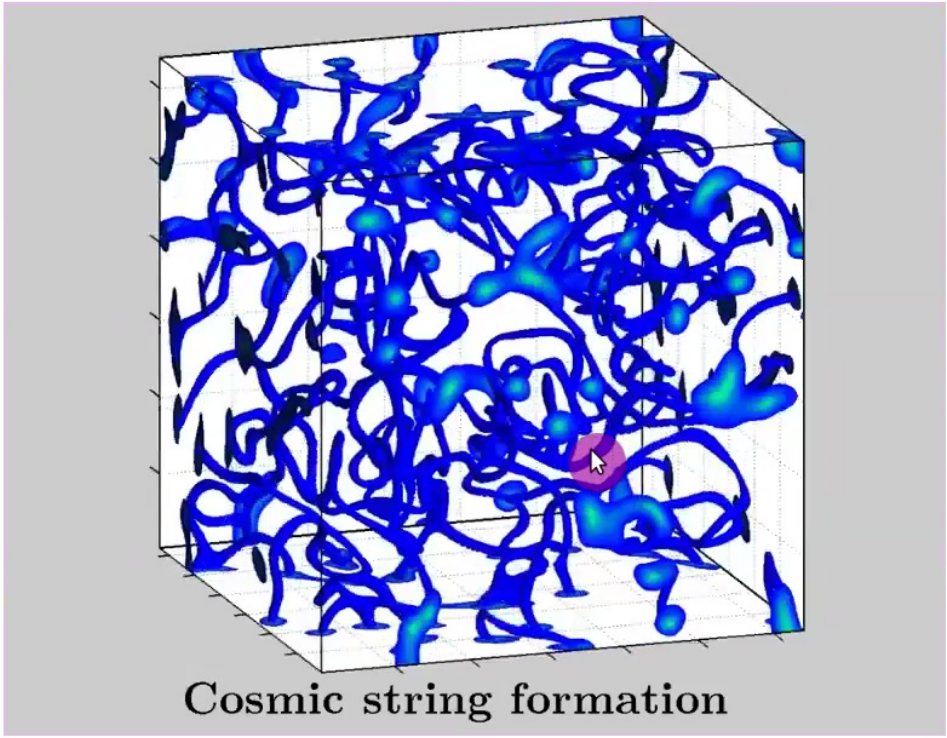
Formation



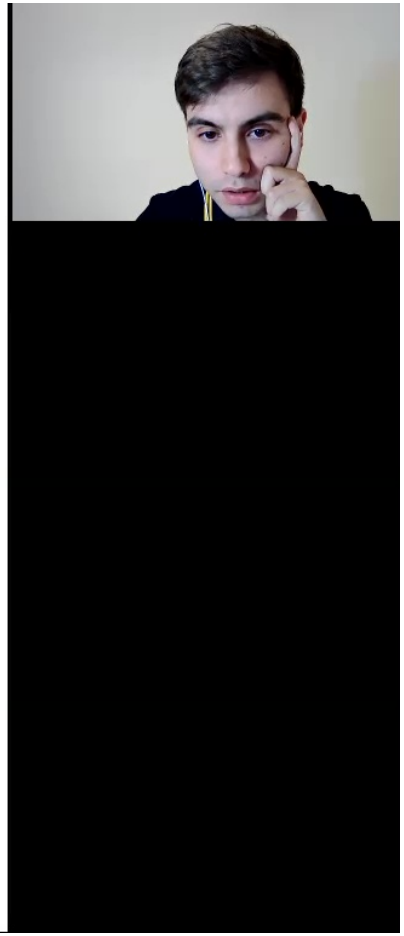
Credit:
Ciaran O'Hare



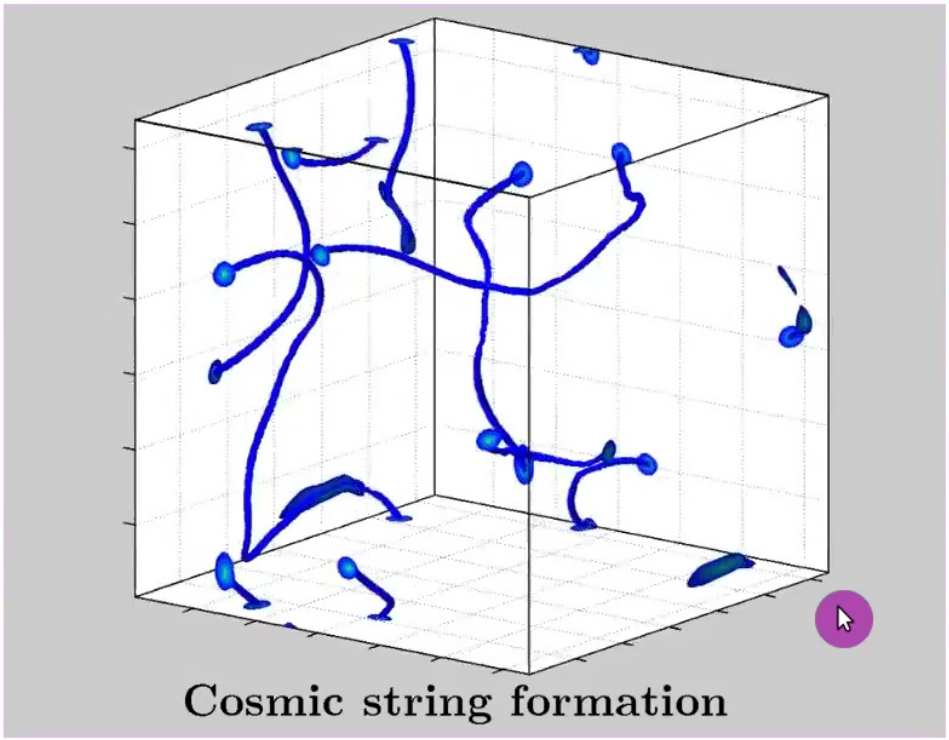
Formation



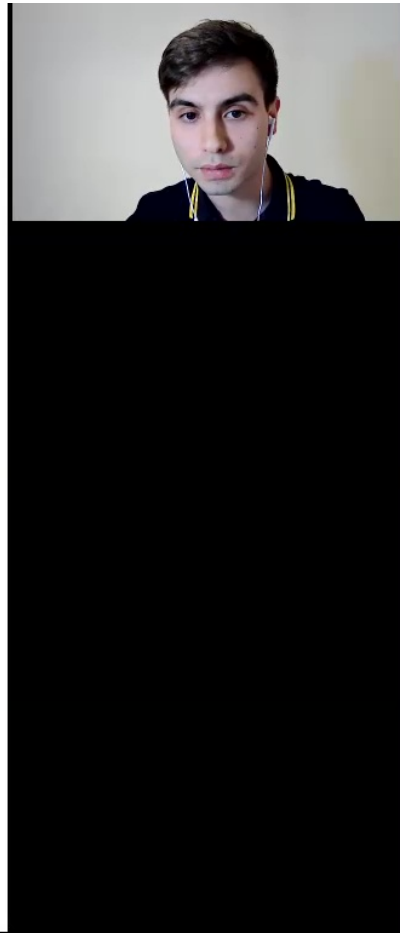
Credit:
Ciaran O'Hare



Formation



Credit:
Ciaran O'Hare



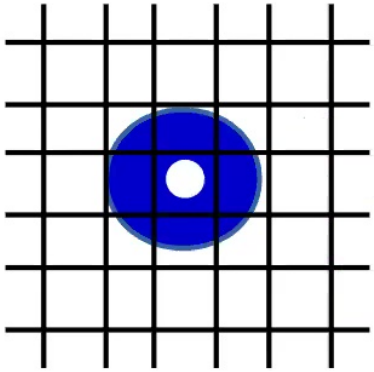
Past work

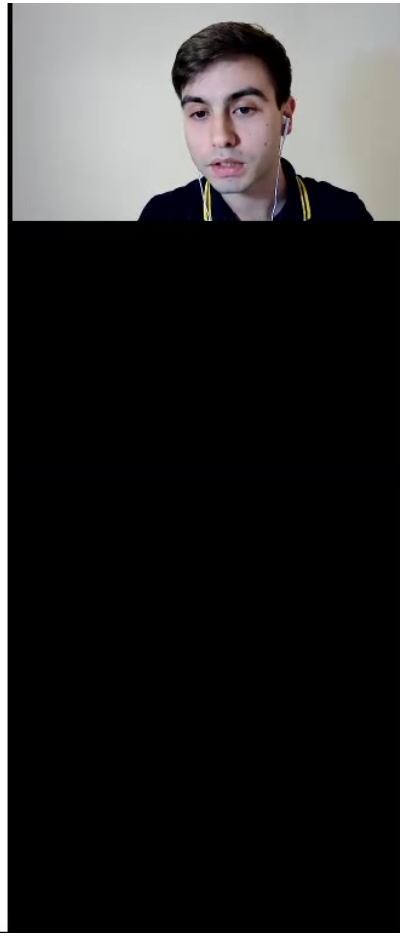
- Field theory approach

- Nambu-Goto approach

Past work

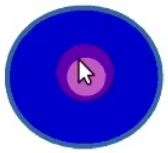
- Field theory approach
  - Take into account field interactions
  - Strings not well resolved ¿?
- Nambu-Goto approach





Past work

- Field theory approach
  - Take into account field interactions
  - Strings not well resolved ¿?
- Nambu-Goto approach



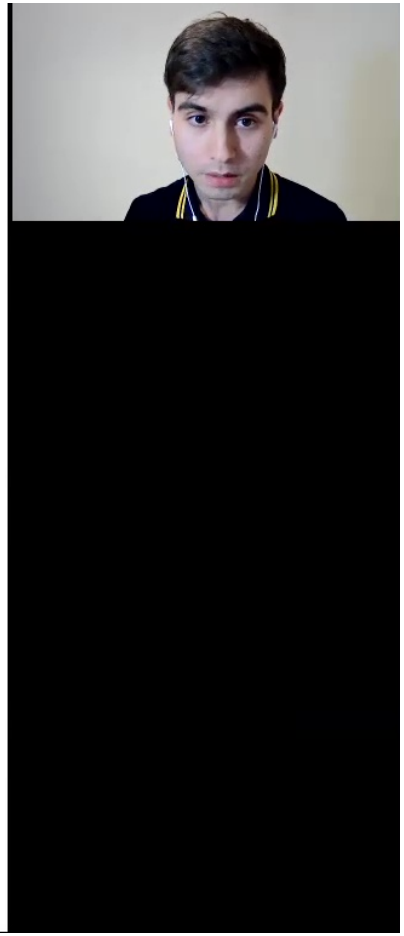
Past work

- Field theory approach
  - Take into account field interactions
  - Strings not well resolved ¿?
- Nambu-Goto approach
  - Can simulate large systems
  - Maybe not capturing all physics ¿?

Past work

- Field theory approach
  - Take into account field interactions
  - Things not well resolved ¿?
- Nambu-Goto approach
  - Can simulate large systems
  - Maybe not capturing all physics ¿?

Different results



Past work

- Field theory approach
  - Take into account field interactions
  - Things not well resolved ¿?
- Nambu-Goto approach
  - Can simulate large systems
  - Maybe not capturing all physics ¿?

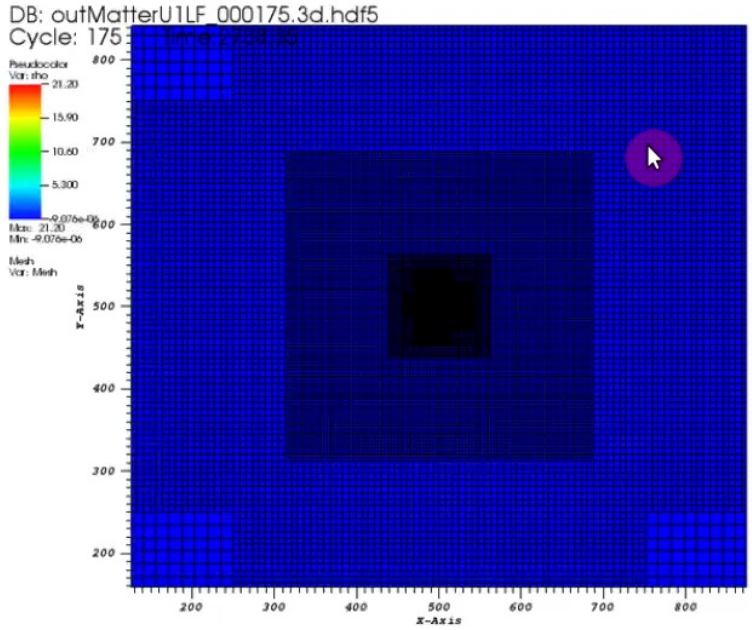
Different results

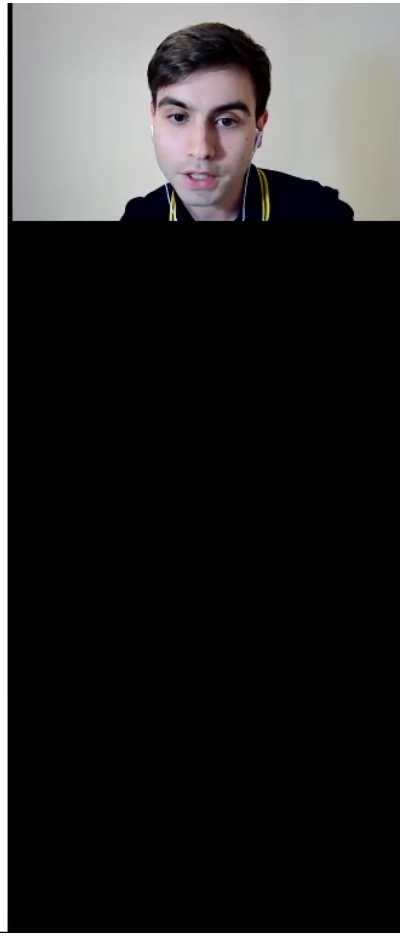
Field theory with
Adaptive Mesh Refinement!

Amelia Drew and Paul Shellard
1910.01718 [astro-ph]

Our work

+ General Relativity [with AMR]





Our work

+ General Relativity [with AMR]

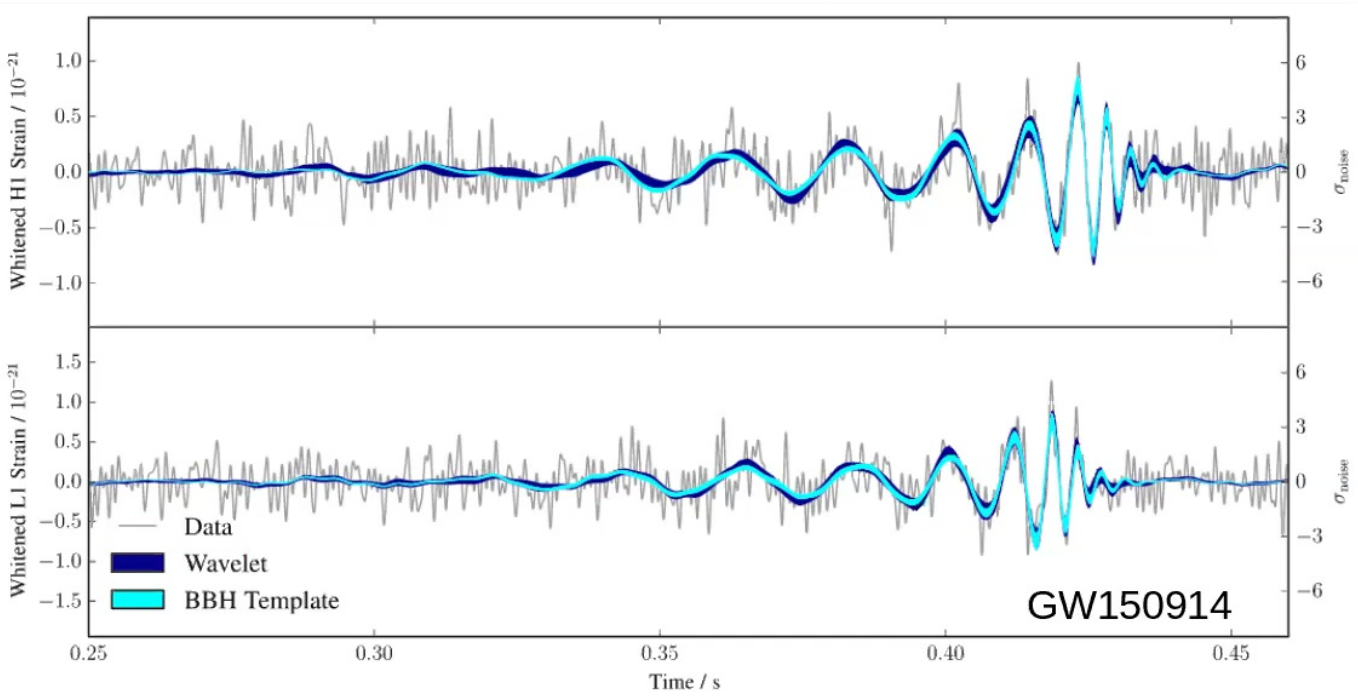
- Capture field interactions with full backreaction effects
  - Can study strong gravity phenomena
    - Black hole formation
    - waveforms!

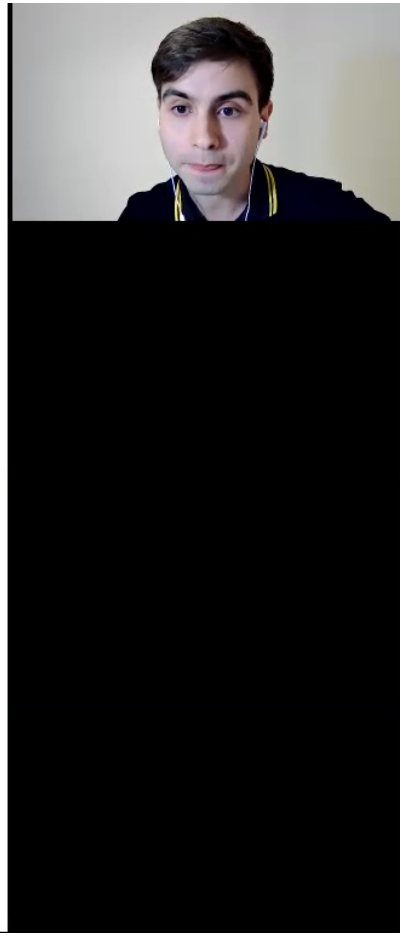
Our work

+ General Relativity [with AMR]

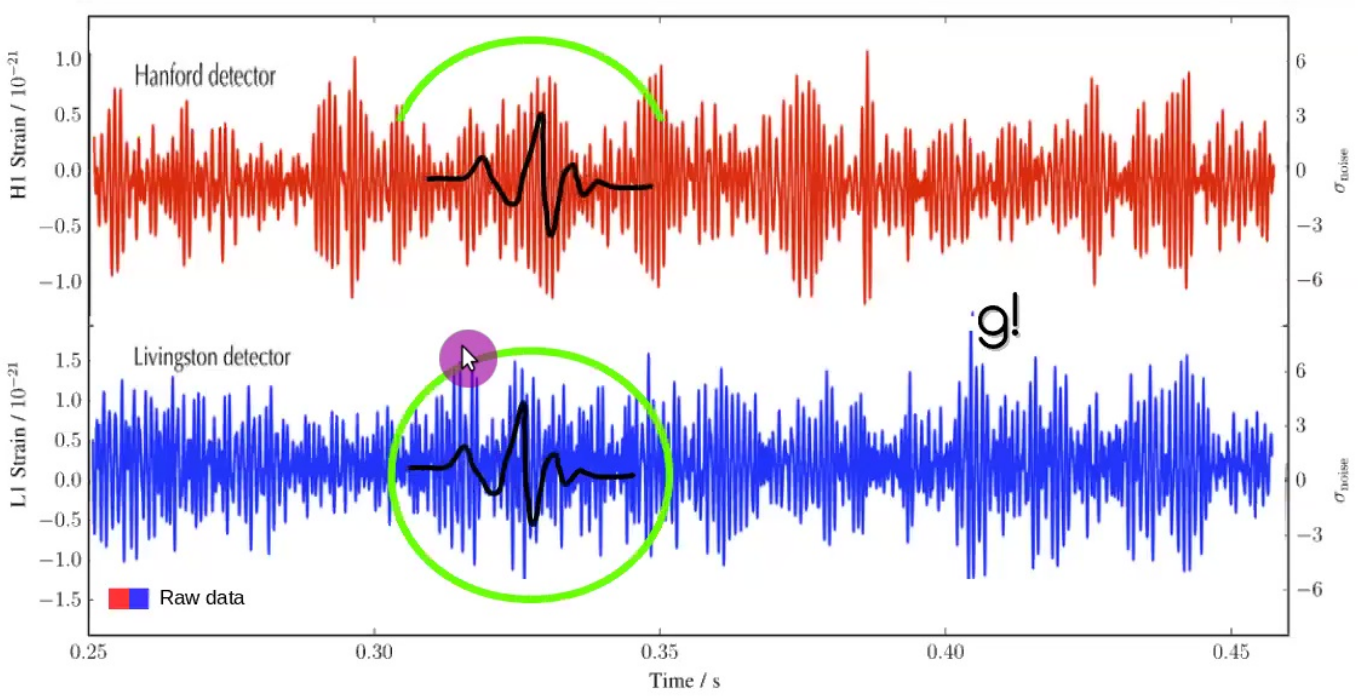
- Capture field interactions with full backreaction effects
  - Can study strong gravity phenomena
    - Black hole formation
    - waveforms!
- Computational limitations
  - Can't simulate networks yet (too expensive)

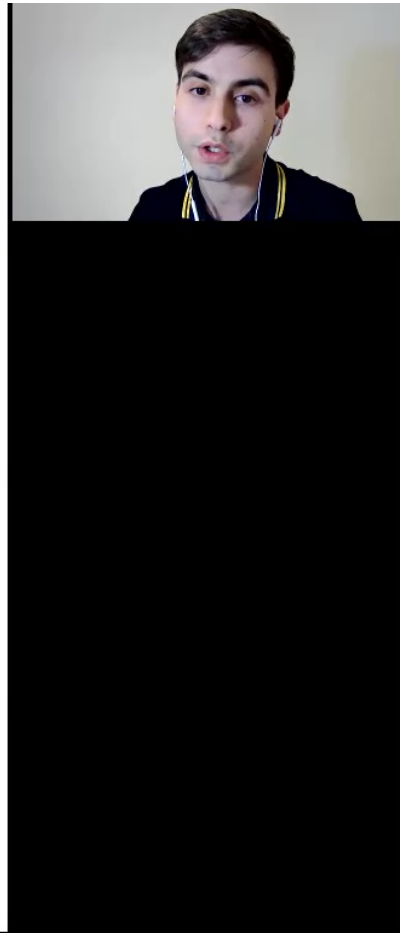
Motivation


Whitened H1 Strain / 10^{-21}
Whitened L1 Strain / 10^{-21}
σ_{noise}
Data
Wavelet
BBH Template
GW150914
Time / s

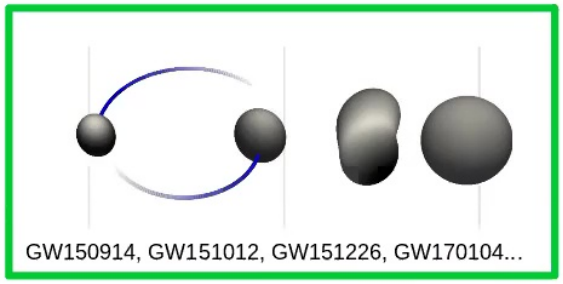
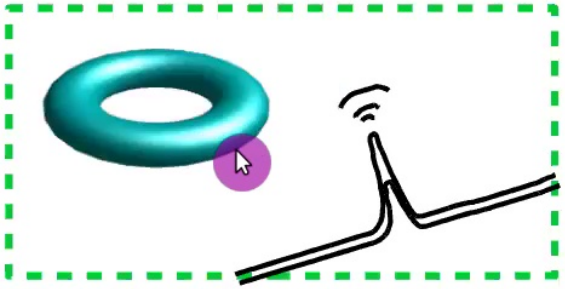


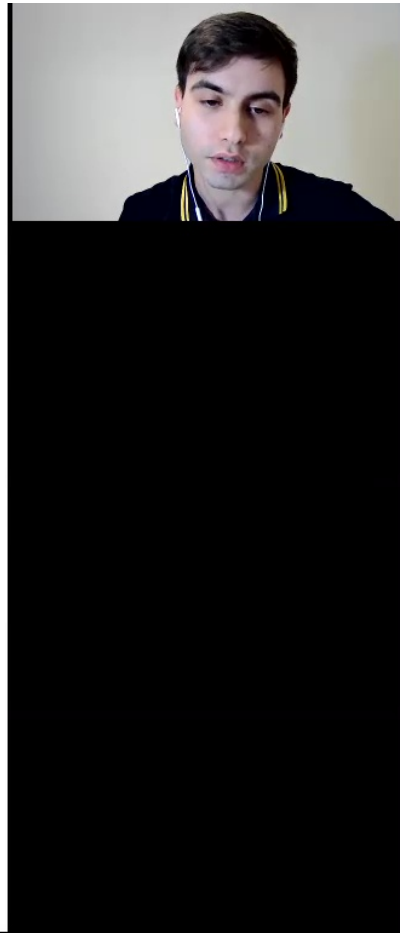
Motivation


Hanford detector
Livingston detector
H1 Strain / 10^{-21}
L1 Strain / 10^{-21}
σ_{noise}
Raw data
Time / s
0.25
0.30
0.35
0.40
0.45
9!



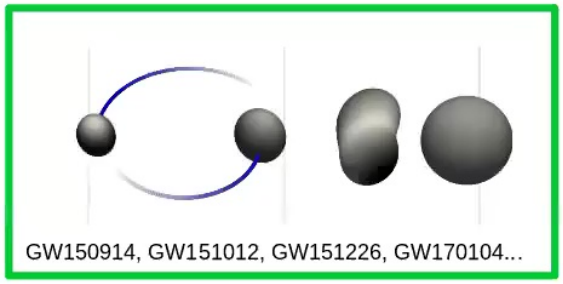
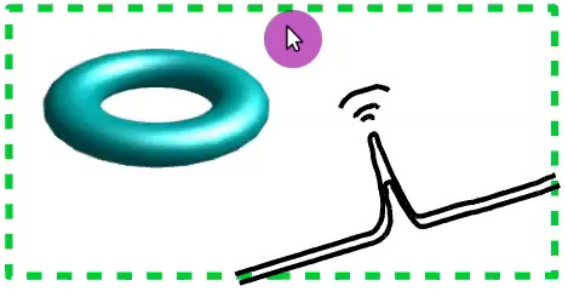
Motivation

	Individual events	Stochastic Background
BBH	 GW150914, GW151012, GW151226, GW170104...	 Jenkins et al. (2018)
Strings		**NO DETECTED**



Numerical Setup

Motivation

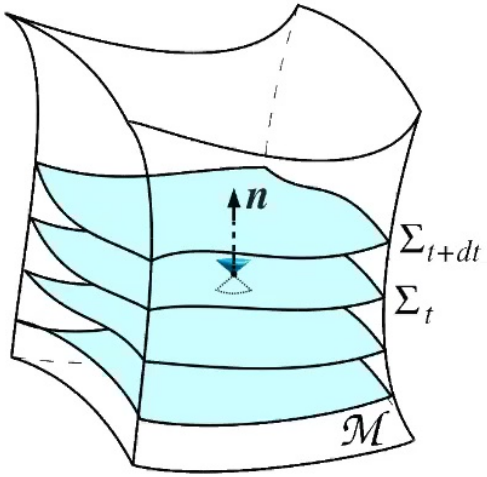
	Individual events	Stochastic Background
BBH	 GW150914, GW151012, GW151226, GW170104...	 Jenkins et al. (2018)
Strings		**NO DETECTED**

Numerical Setup

Gravity sector

$$ds^2 = -\alpha^2 dt^2 + \gamma_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt)$$

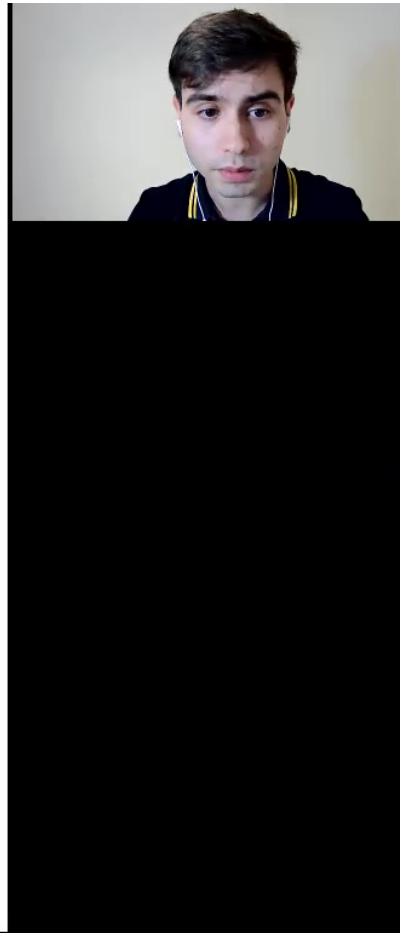
lapse 3-metric shift



Extrinsic curvature

$$K_{ij} = \mathcal{L}_{\mathbf{n}}\gamma_{ij} \sim \dot{\gamma}_{ij}$$

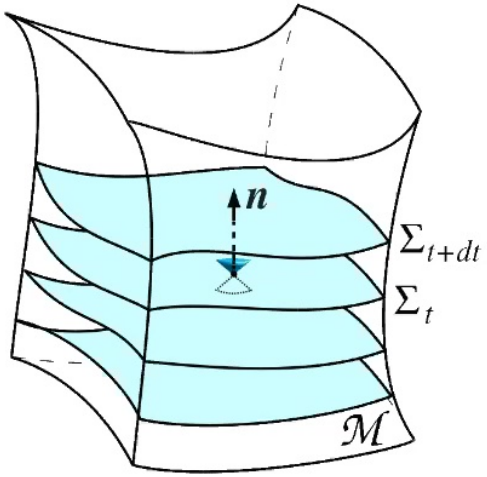
$$K = \mathrm{Tr}K_{ij}$$ (Hubble parameter in FRW)



Gravity sector

$$ds^2 = -\alpha^2 dt^2 + \gamma_{ij}(dx^i + \beta^i dt)(dx^j + \beta^j dt)$$

lapse 3-metric shift



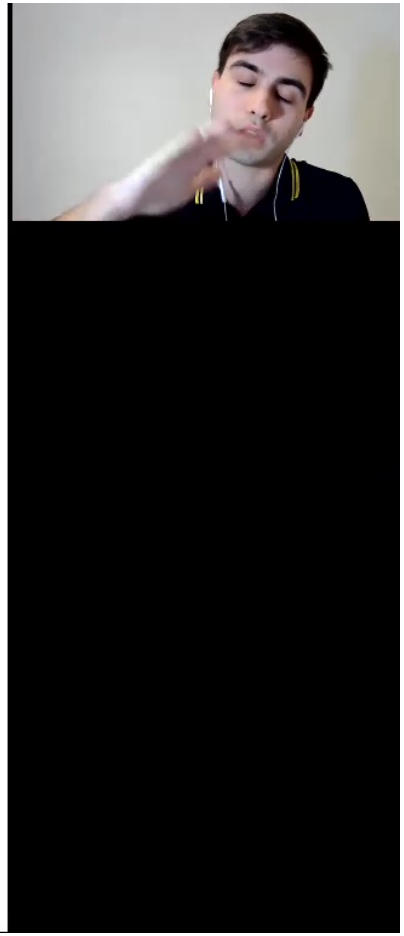
Extrinsic curvature

$$K_{ij} = \mathcal{L}_{\mathbf{n}}\gamma_{ij} \sim \dot{\gamma}_{ij}$$

$K = \mathrm{Tr}K_{ij}$ (Hubble parameter in FRW)

Projector

$$P^{\nu}_{\mu} = \delta^{\nu}_{\mu} + n_{\mu}n^{\nu}$$



Gravity sector

4 constraint equations

energy density

Hamiltonian $\mathcal{H} = R + K^2 - K_{ij}K^{ij} - 16\pi\rho = 0$

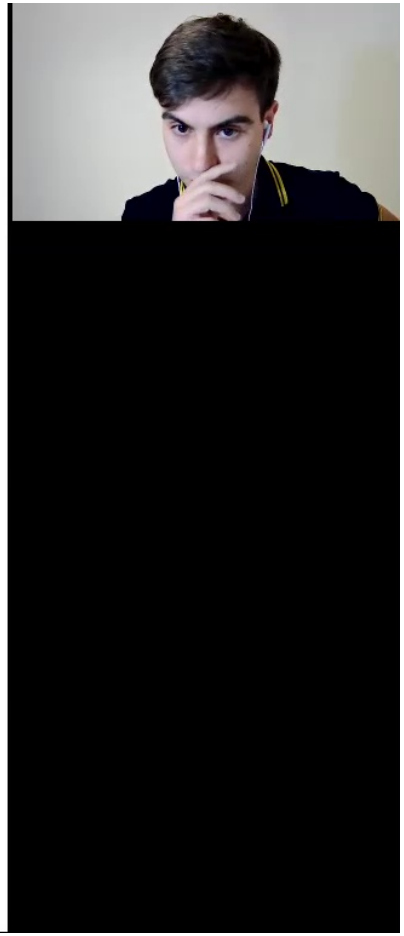
Momentum $\mathcal{M}_i = D^j\left(\gamma_{ij}K - K_{ij}\right) - 8\pi S_i = 0$

momentum density

Evolution equations:

BSSN formulation

initial data → evolve

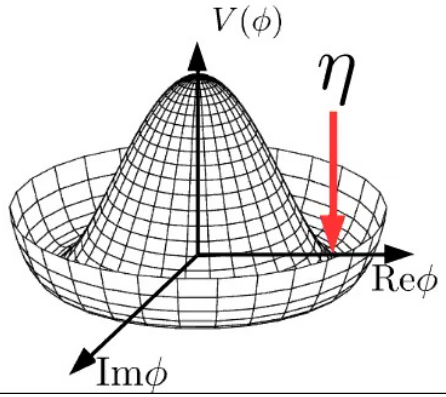


Matter sector

Abelian Higgs $$\mathcal{L} = -\underbrace{(D_\mu\phi)^*(D^\mu\phi) - V(\phi)}_{\text{Complex scalar}} - \underbrace{\frac{1}{4}F_{\mu\nu}F^{\mu\nu}}_{\text{Gauge field}}$$

$$D_\mu = \partial_\mu - ieA_\mu$$

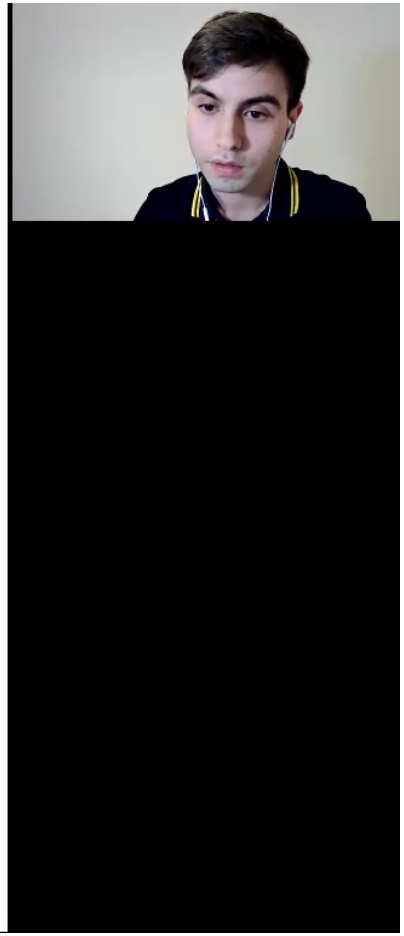
$$J^\mu = 2\mathrm{Im}\left(\phi^* D^\mu \phi\right)$$



$$V(\phi) = \frac{1}{4}\lambda\left(|\phi|^2 - \eta^2\right)^2$$

String tension:

$$G\mu = 2\pi G\eta^2$$



Matter sector

Gauss constraint $\gamma_i^\mu \nabla_\mu E^i = e\mathcal{J}$ $E_\mu = P_\mu^\nu n^\alpha F_{\nu\alpha}$

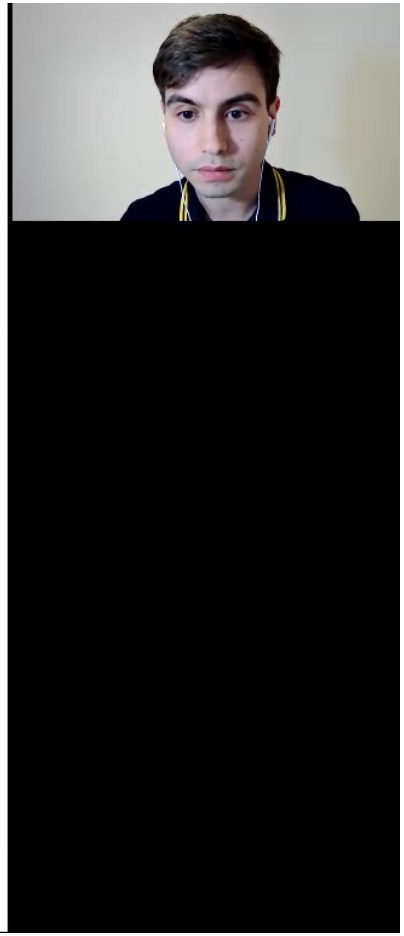
Longitudinal component of J^μ

Knapp-Walker-Baumgarte formalism

Introduce auxiliary variable Z

$$\partial_t Z = \alpha\left(\tilde{\nabla}_i E^i - e\mathcal{J} - \kappa Z\right) + \beta^j \partial_j Z \qquad Z \to 0$$

Damping constant



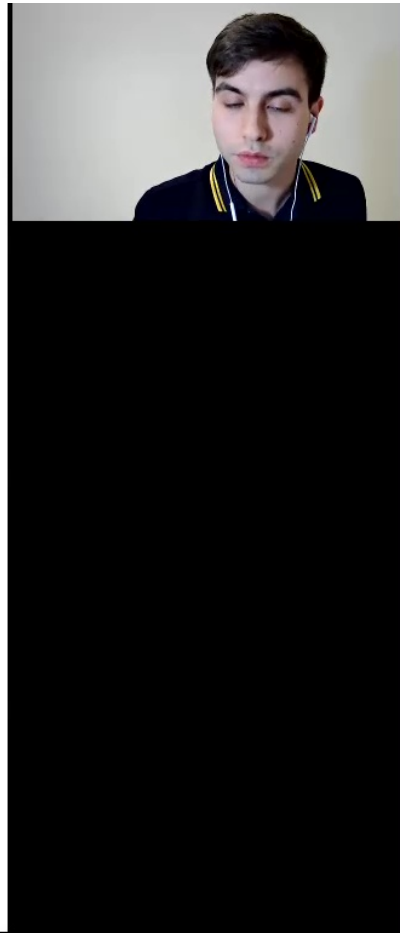
How to:

Once evolution equations are coded,

Study different phenomena:

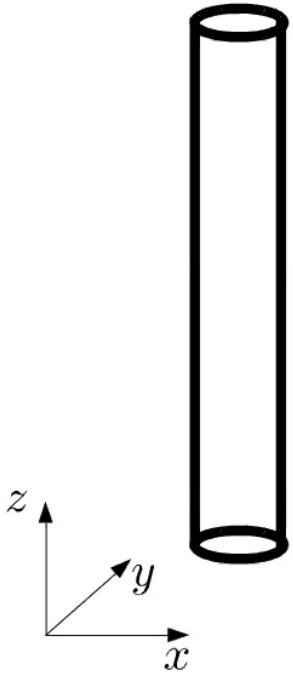
Infinite static string:

Solve constraints → evolve



Infinite Static String

Initial Data

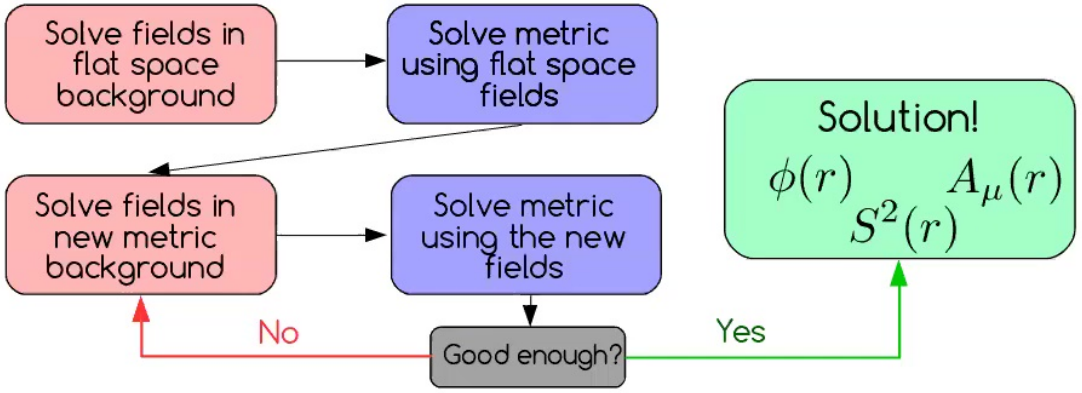


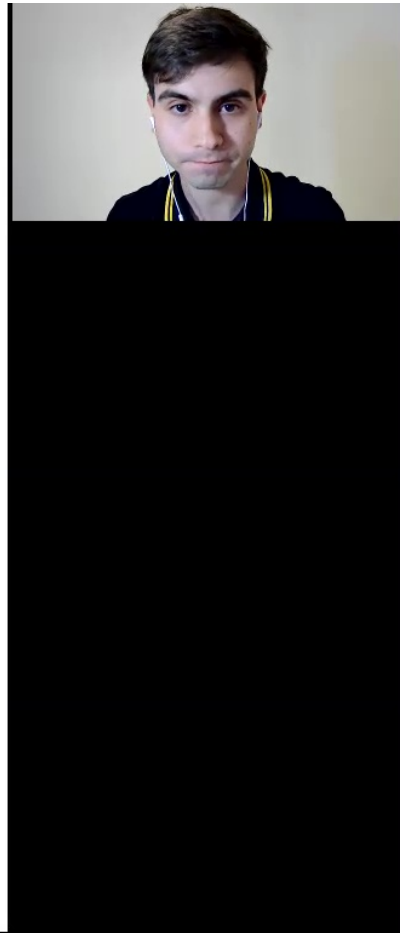
Matter

Einstein

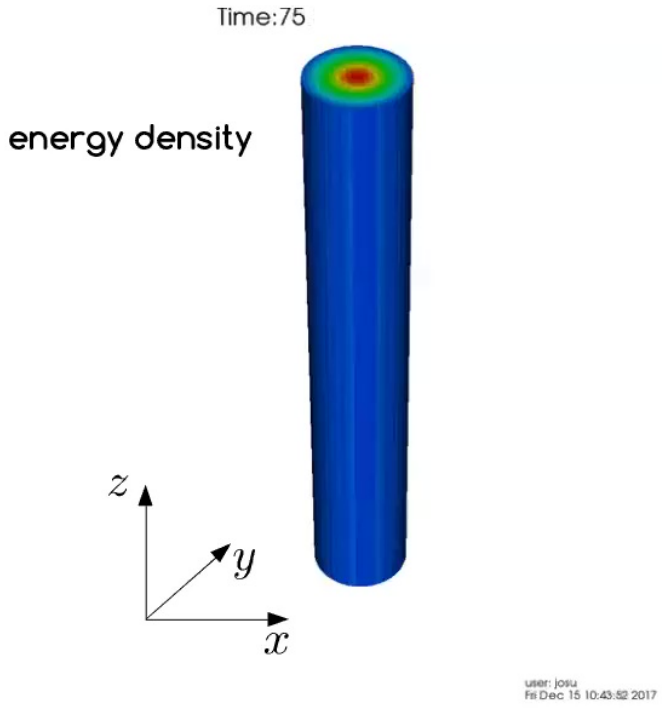
$\phi(r)$ $A_\mu(r)$

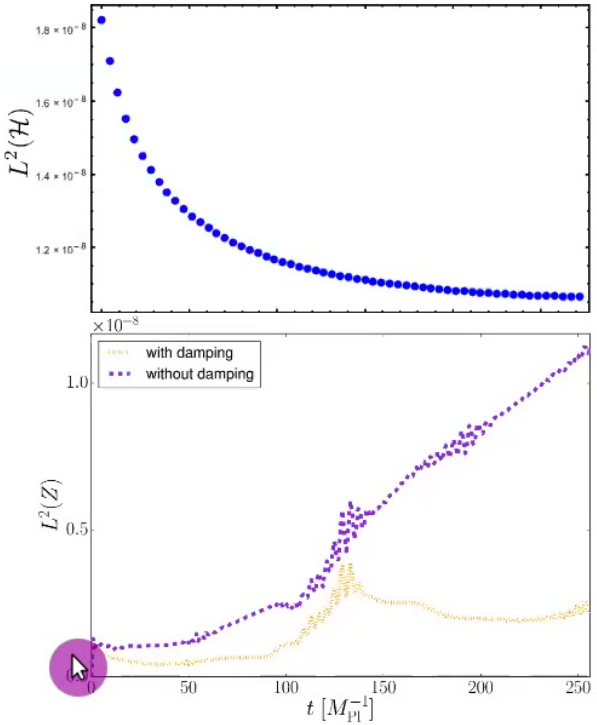
$$ds^2 = -dt^2 + S^2(r)(dr^2 + r^2 d\theta^2) + dz^2$$

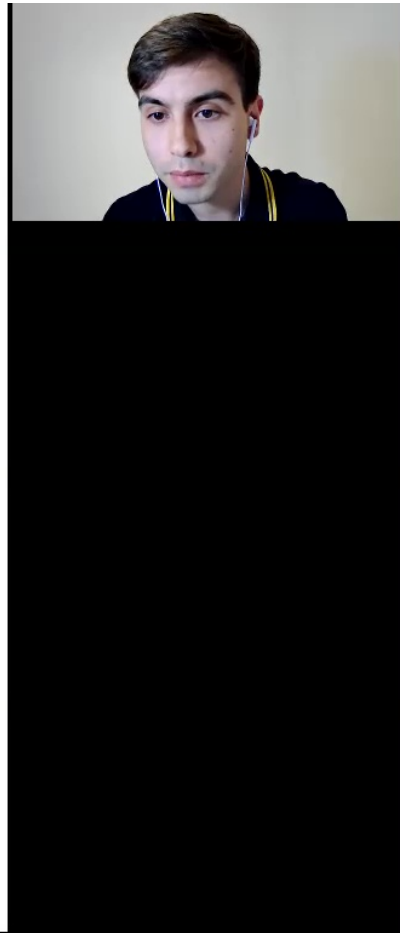




Infinite Static String

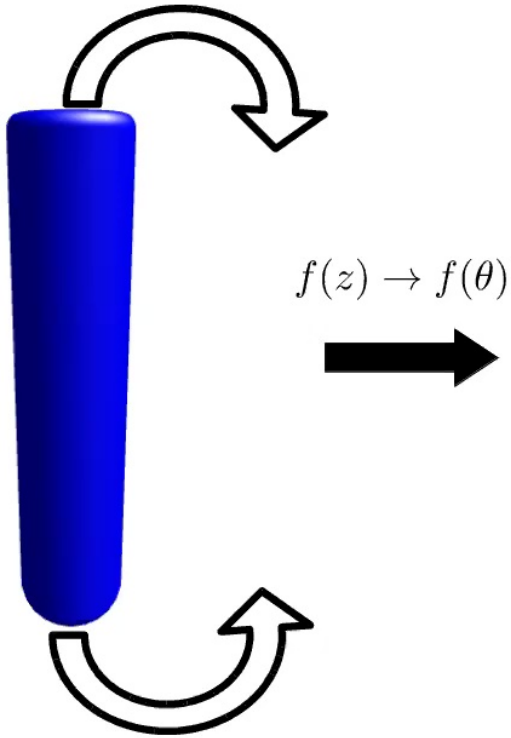






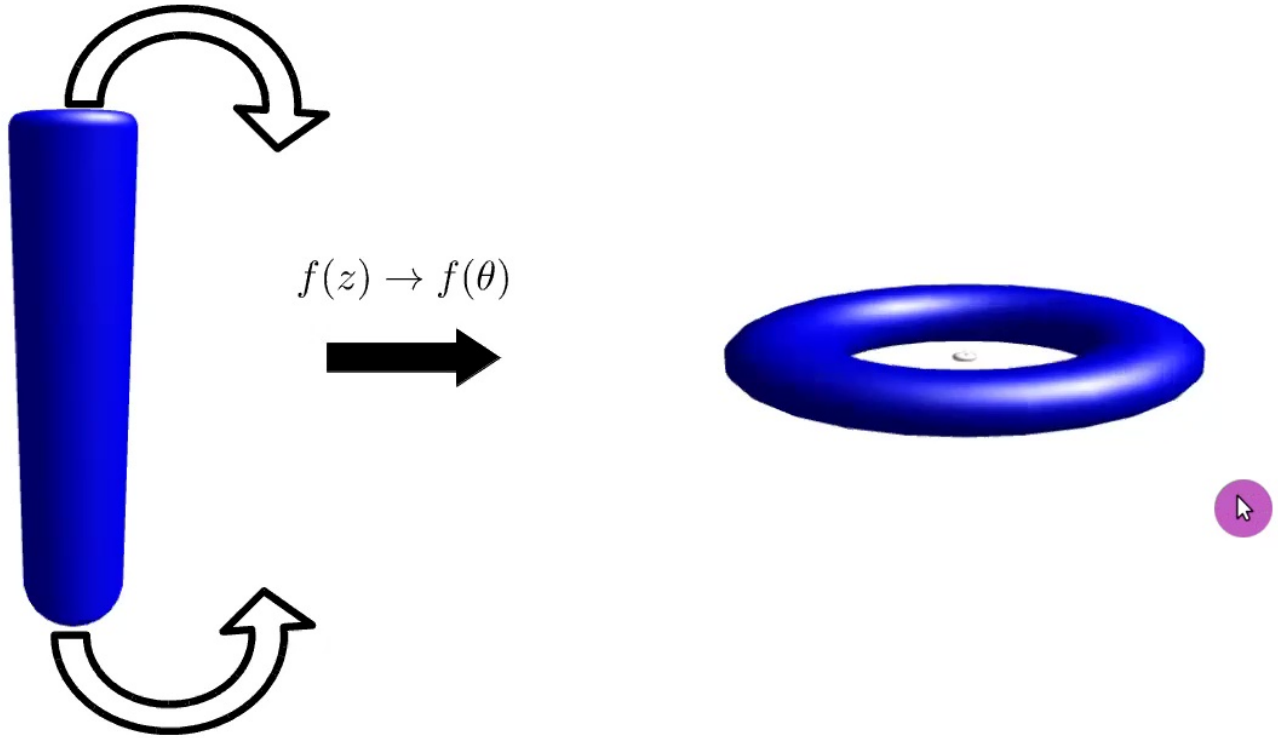
Cosmic String Loop Collapse

Initial Data (Matter)

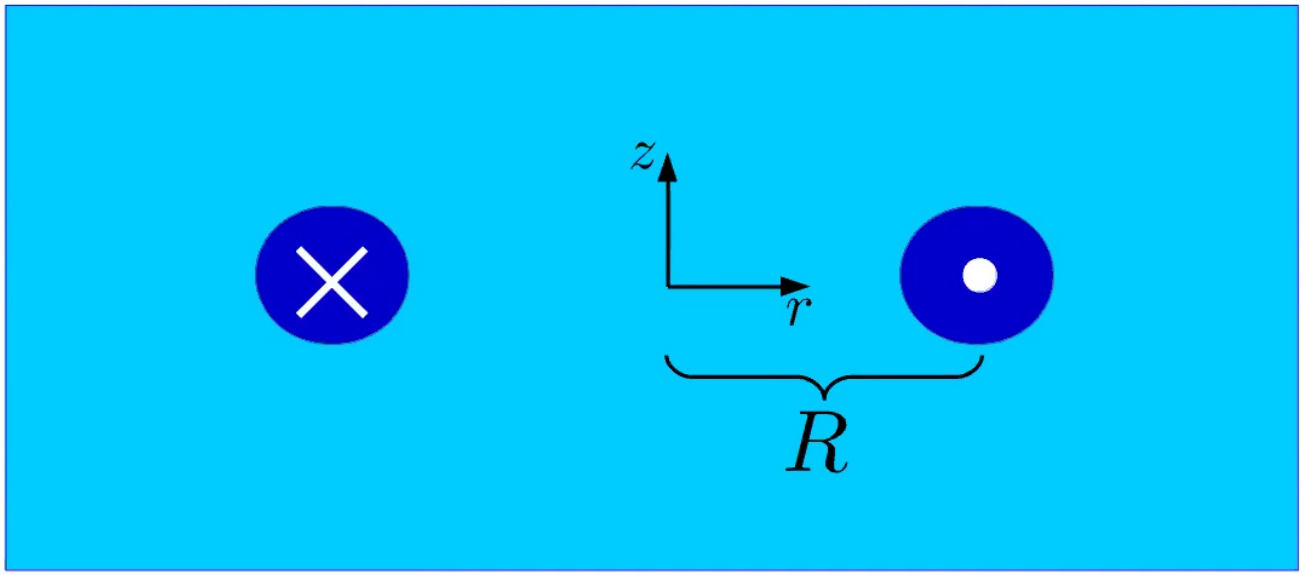


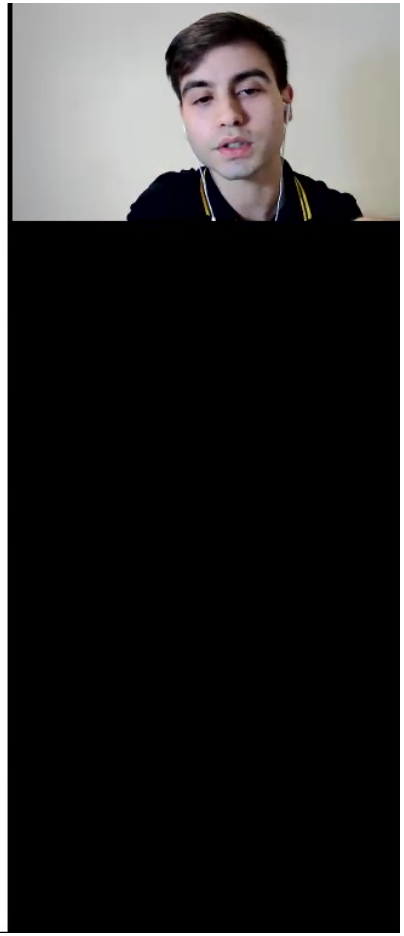
$$f(z) \to f(\theta)$$

Initial Data (Matter)

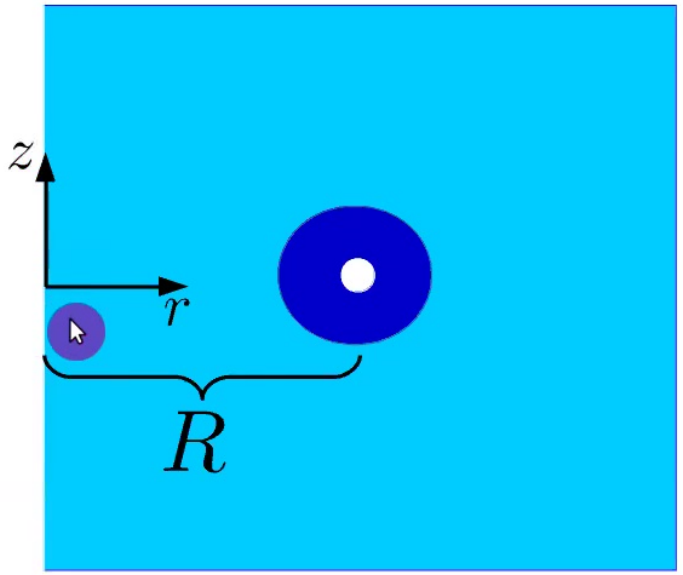


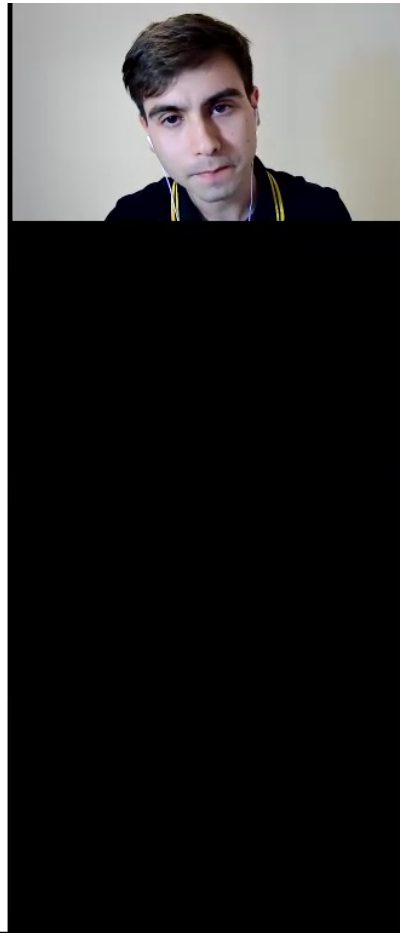
Initial Data (Gravity)





Initial Data (Gravity)





Initial Data (Gravity)

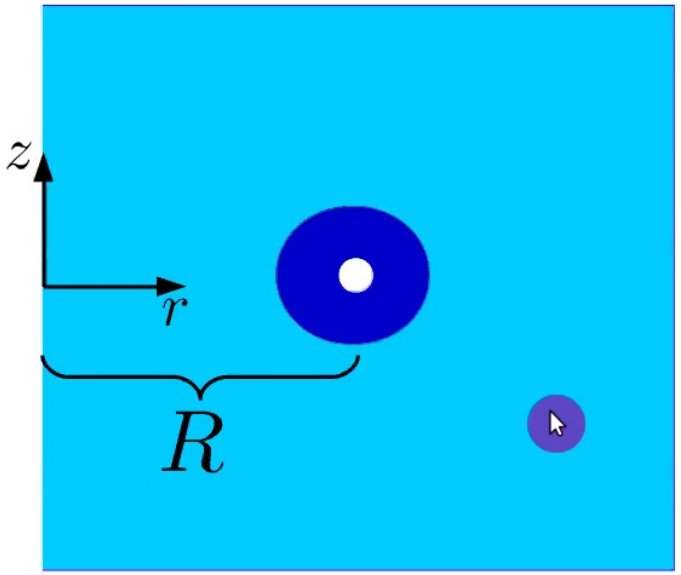
$$\gamma_{ij}dx^i dx^j = \frac{1}{\chi}(dr^2 + r^2 d\theta^2 + dz^2)$$

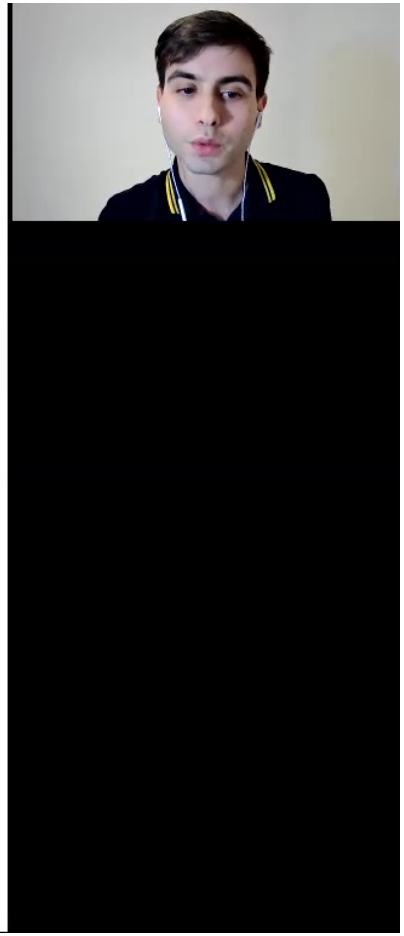
Solve Ham constraint

$$R + K^2 - K_{ij}K^{ij} - 16\pi\rho = 0$$

Mom constraints satisfied

$$\mathcal{M}_i = 0$$



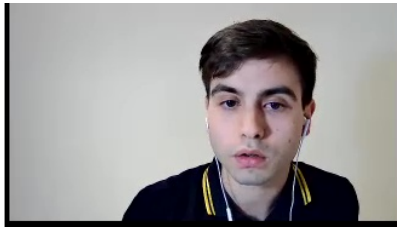


Recap

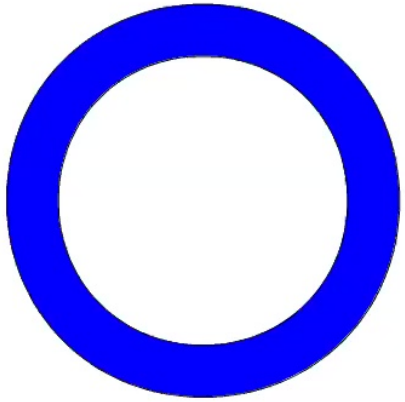
Bigger parameter space

String $\Longrightarrow$ $G\mu$ ↑ Mass ↑

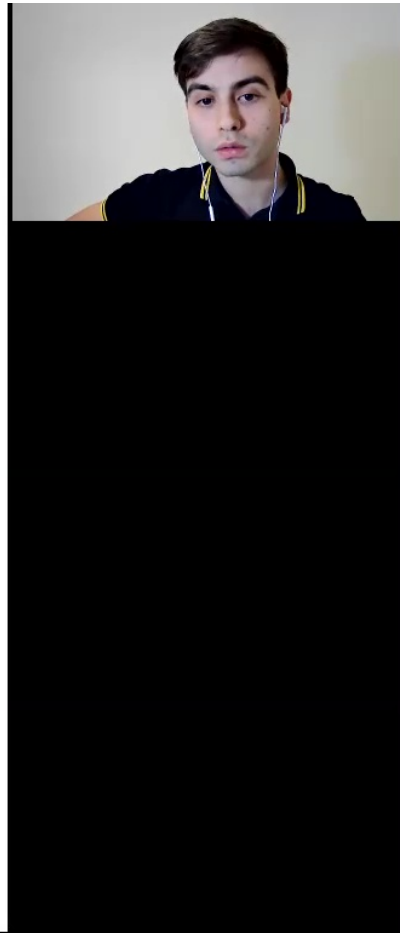
String loop $\Longrightarrow$ $(G\mu,\ R)$ ↑ Mass ↑



String Loop Collapse

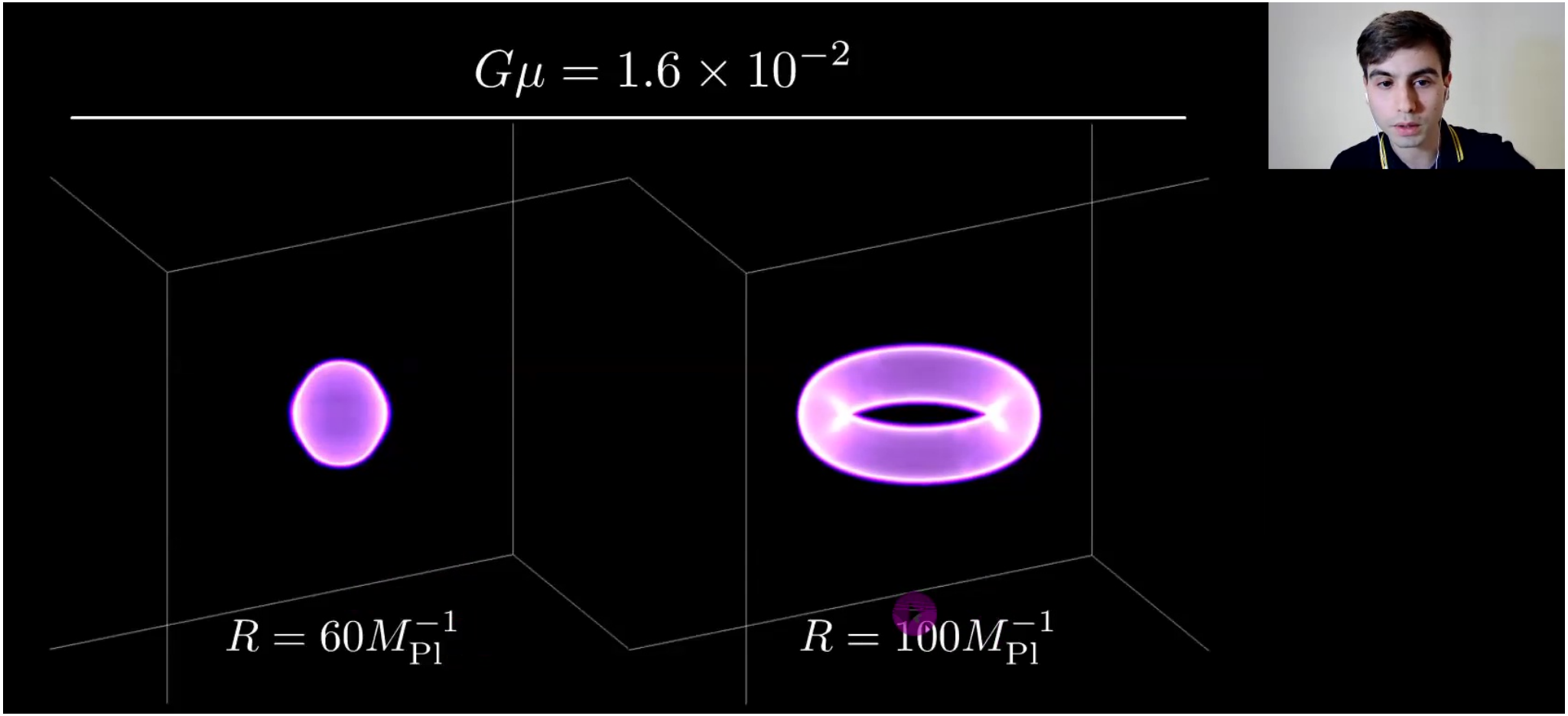


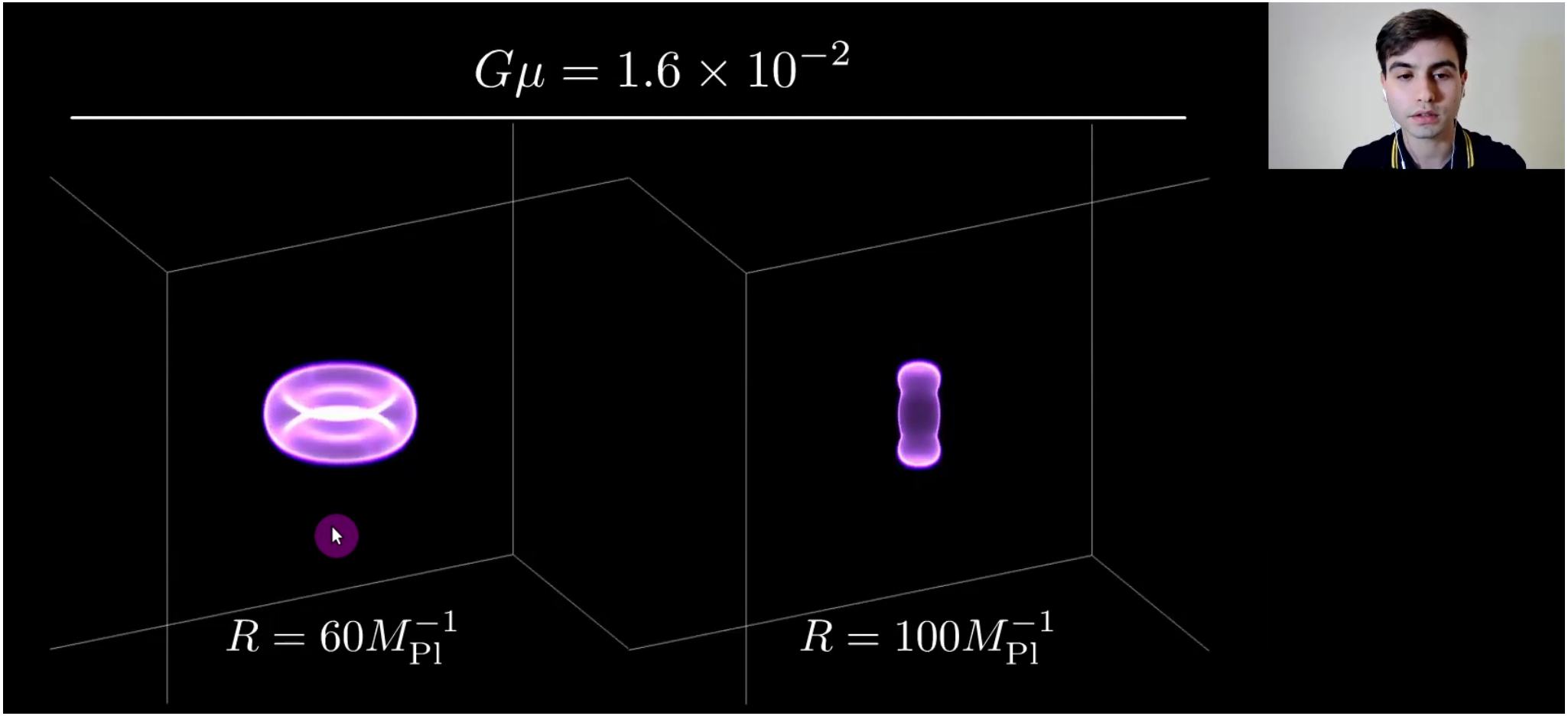
$$M_0 = 2\pi R\mu$$

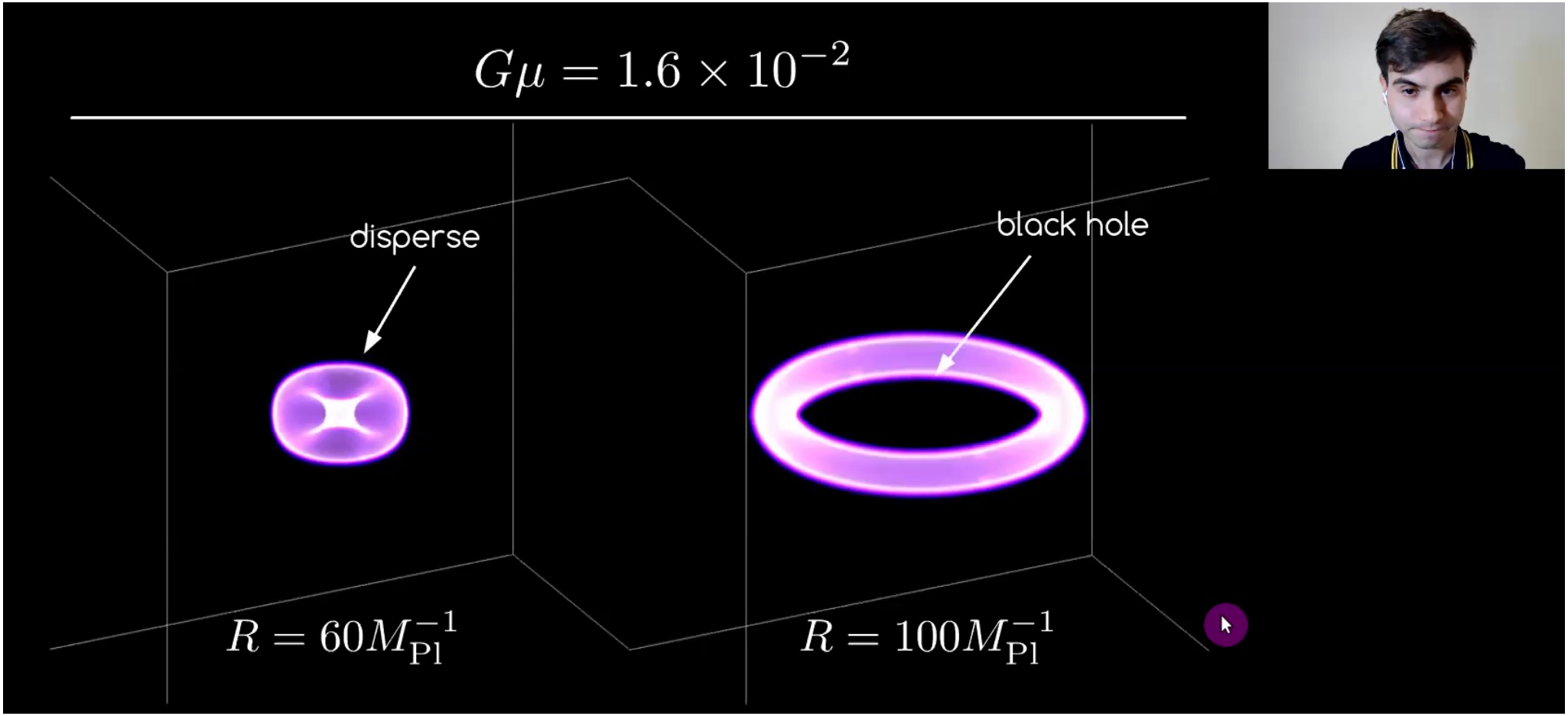


String Loop Collapse

$$M_0 = 2\pi R\mu$$

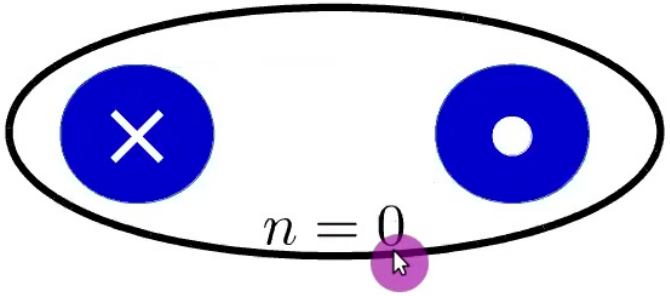

$G\mu = 1.6 \times 10^{-2}$
$R = 60 M_{\rm Pl}^{-1}$
$R = 100 M_{\rm Pl}^{-1}$


$G\mu = 1.6 \times 10^{-2}$
$R = 60 M_{\rm Pl}^{-1}$
$R = 100 M_{\rm Pl}^{-1}$

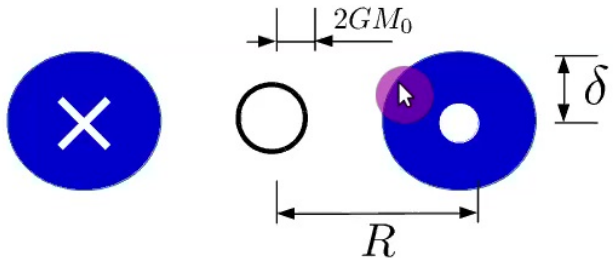

$G\mu = 1.6 \times 10^{-2}$
disperse
black hole
$R = 60 M_{\rm Pl}^{-1}$
$R = 100 M_{\rm Pl}^{-1}$

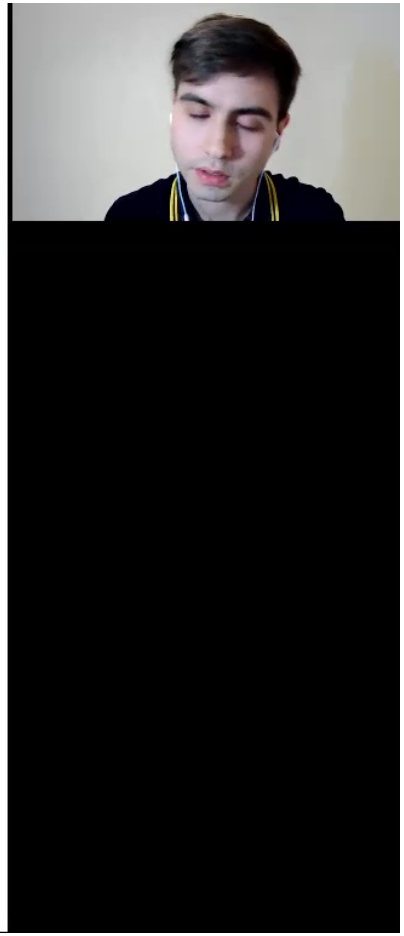
String Loop Collapse

String Loop Collapse

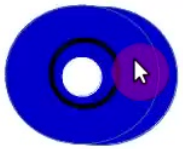


String Loop Collapse

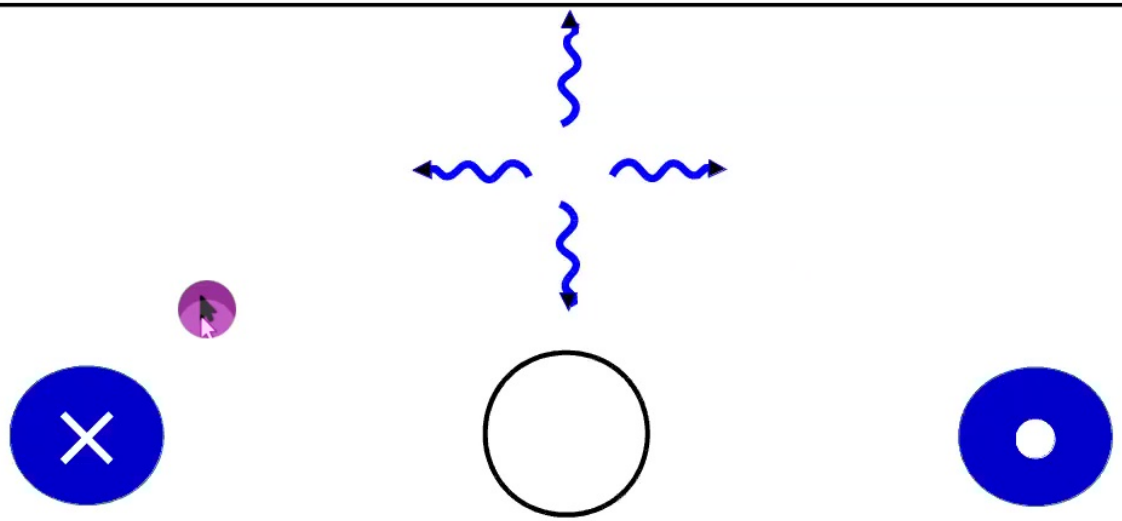


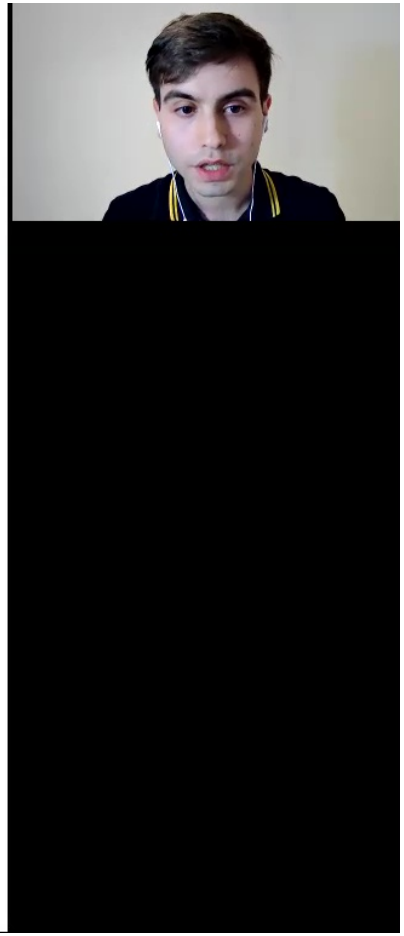


String Loop Collapse

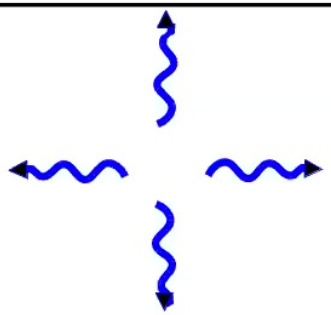


String Loop Collapse

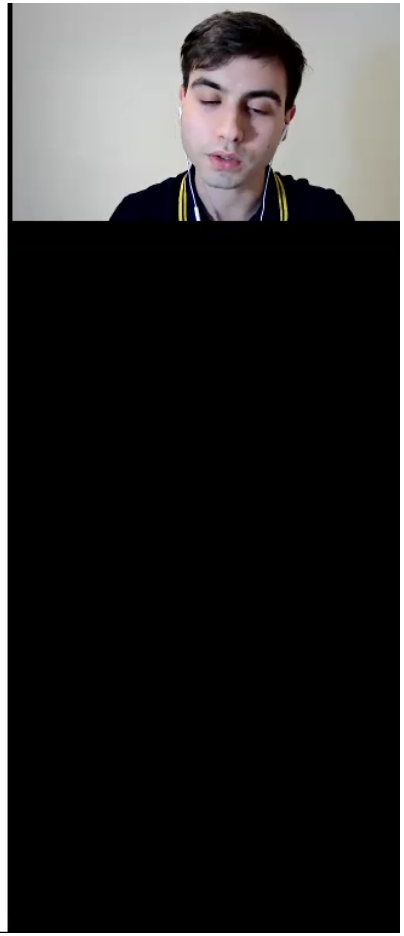




String Loop Collapse



$$2GM_0 > \delta \quad \Rightarrow \quad R > \sqrt{\frac{1}{8\pi\lambda}}(G\mu)^{-3/2}M_{pl}^{-1}$$



String Loop Collapse

Sensitive in LIGO/Virgo/KAGRA if $M_{\rm BH} \approx 100 M_\odot$

Current bounds

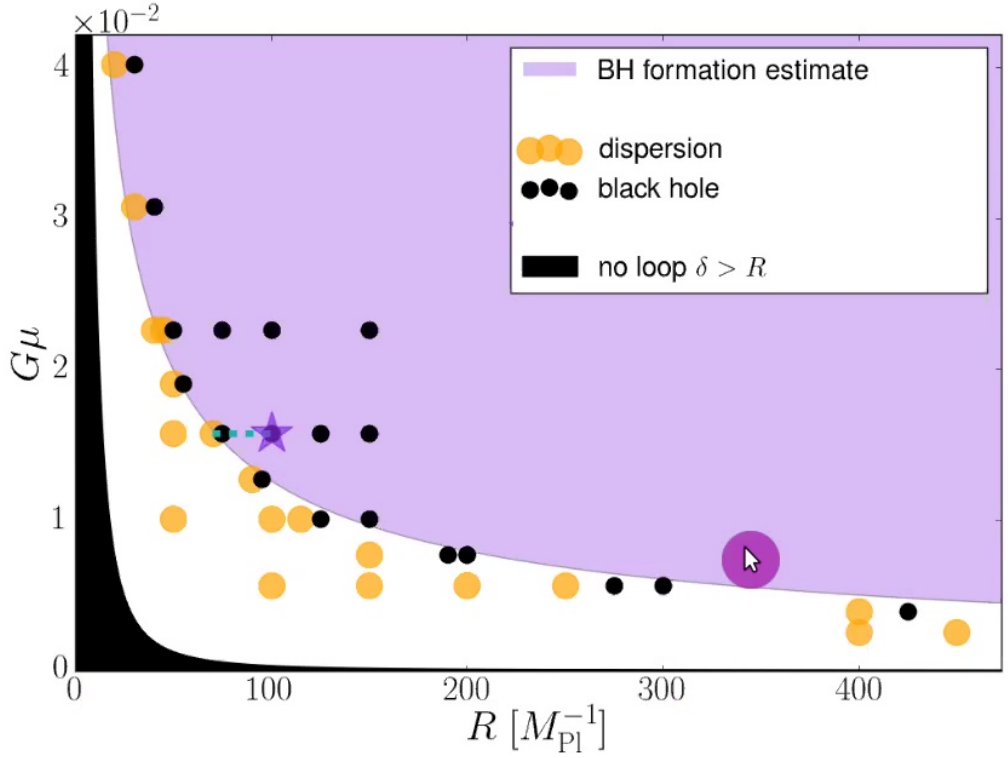
$G\mu \lessapprox 10^{-7} - 10^{-10}$

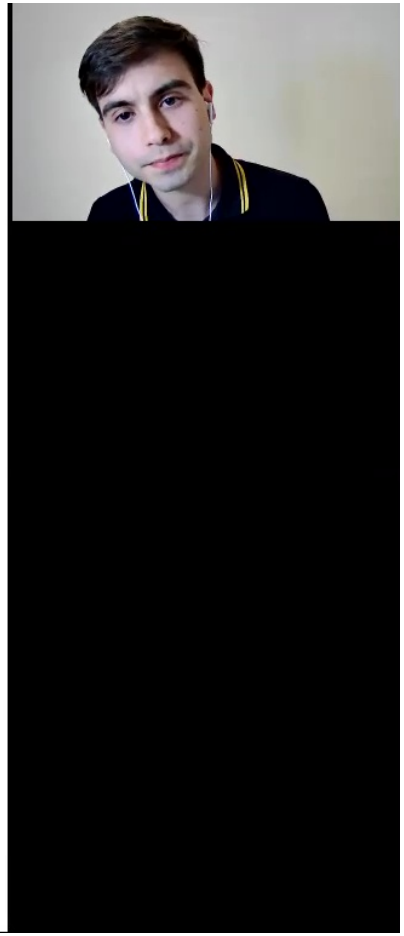
Solar system sized loops!

$R_0 \gtrapprox 1 - 10^3$ a.u

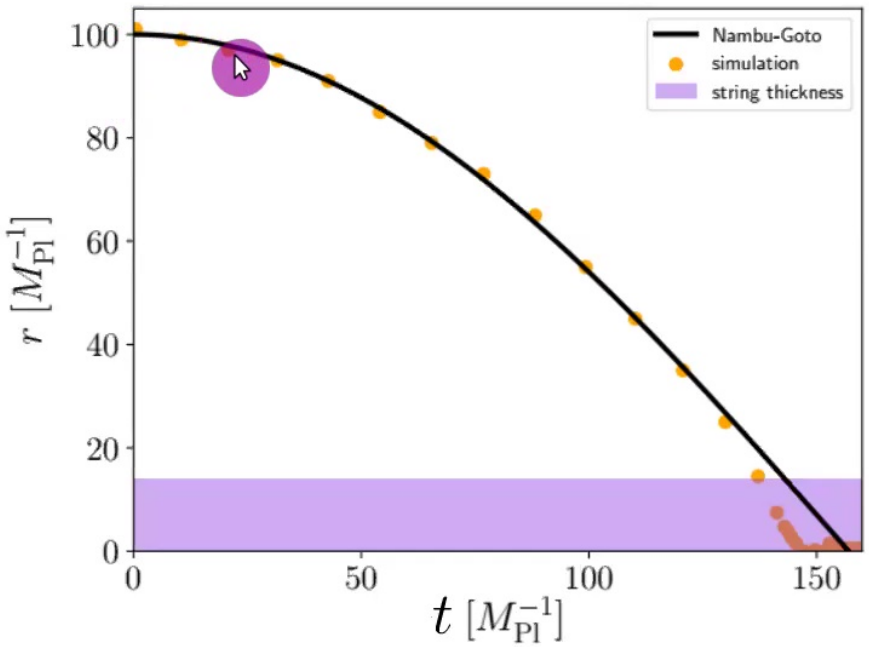
$2GM_0 > \delta$ ➡ $R > \sqrt{\frac{1}{8\pi\lambda}} (G\mu)^{-3/2} M_{pl}^{-1}$

String Loop Collapse



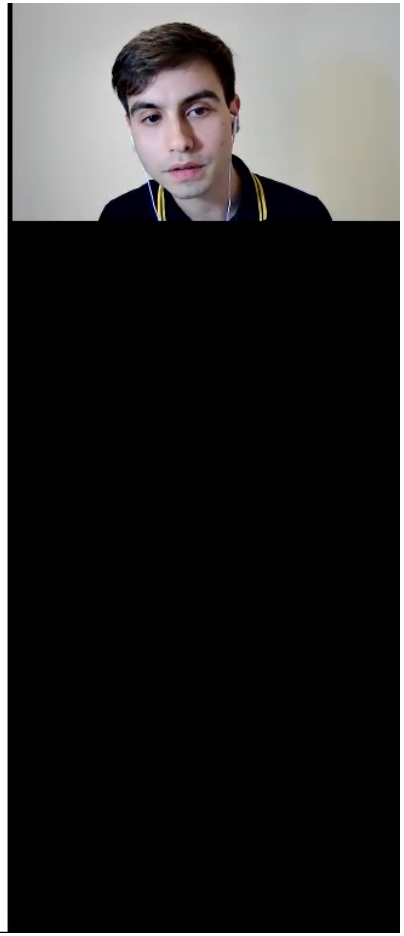


Comparison with Nambu-Goto

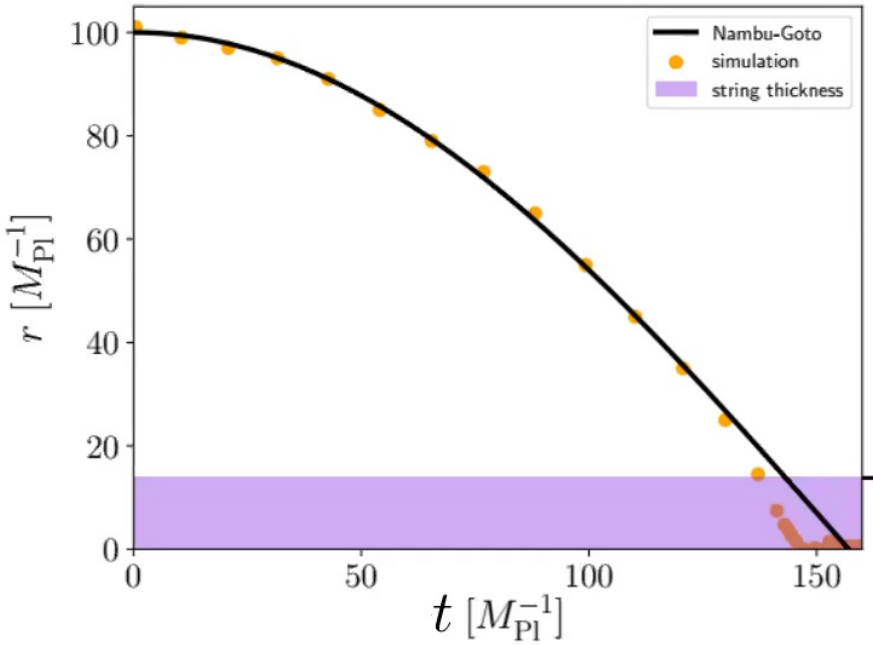


Nambu-Goto loops:

$$r(t) = R\cos\left(\frac{t}{R}\right)$$



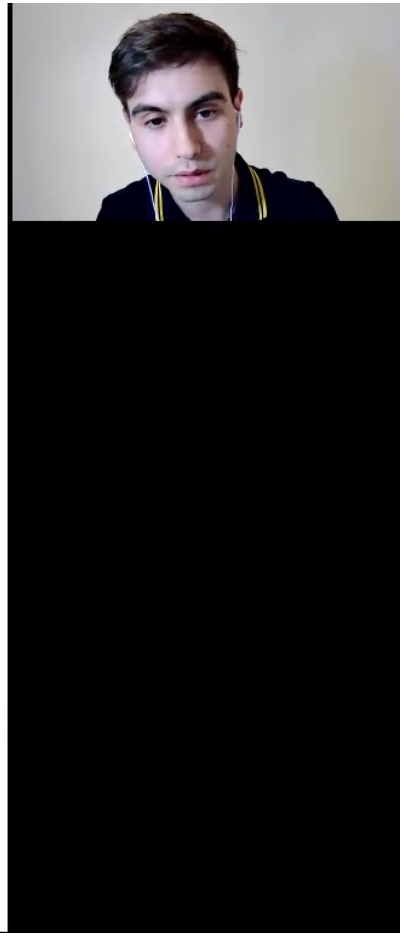
Comparison with Nambu-Goto



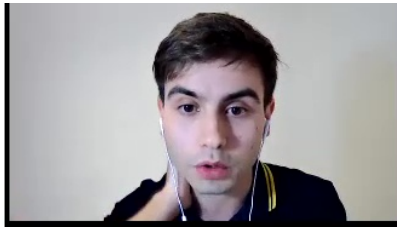
Nambu-Goto loops:

$$r(t) = R\cos\left(\frac{t}{R}\right)$$

$v \approx 0.97c$

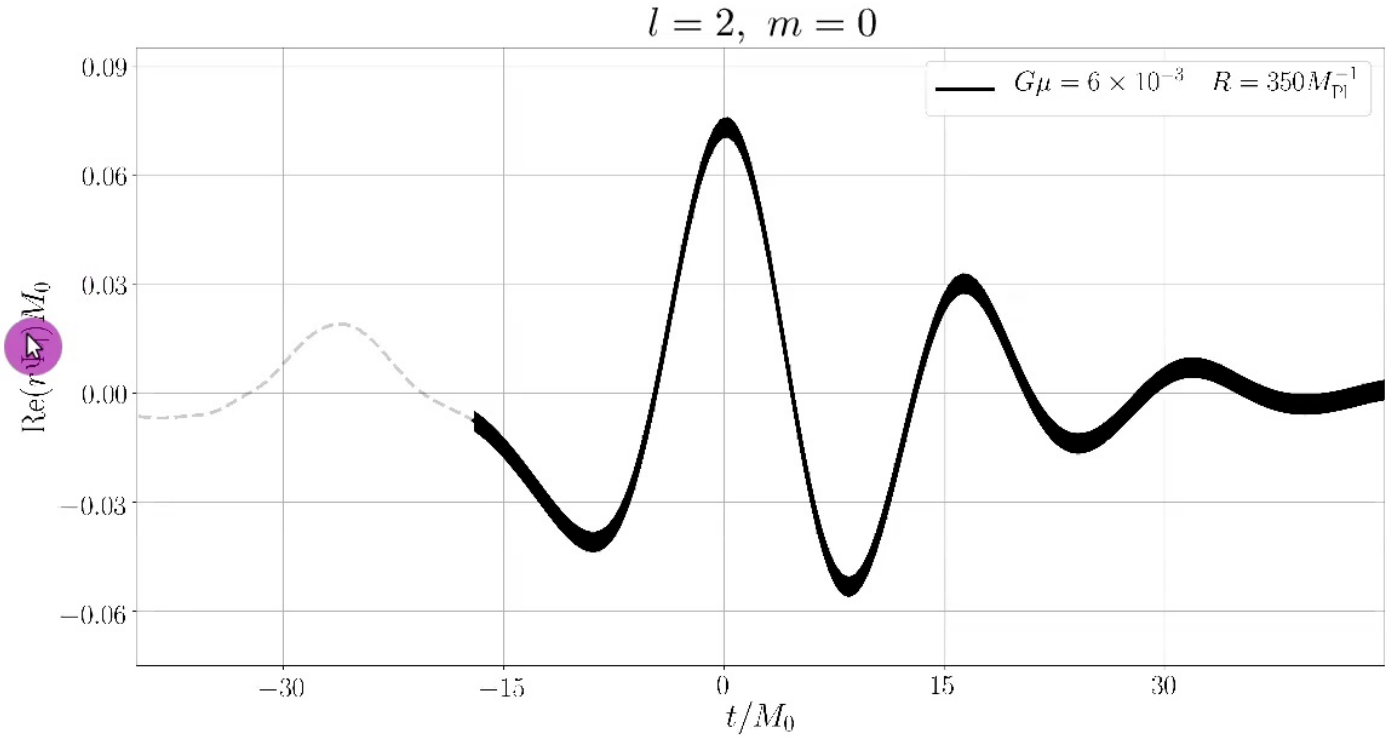


Gravitational Waves

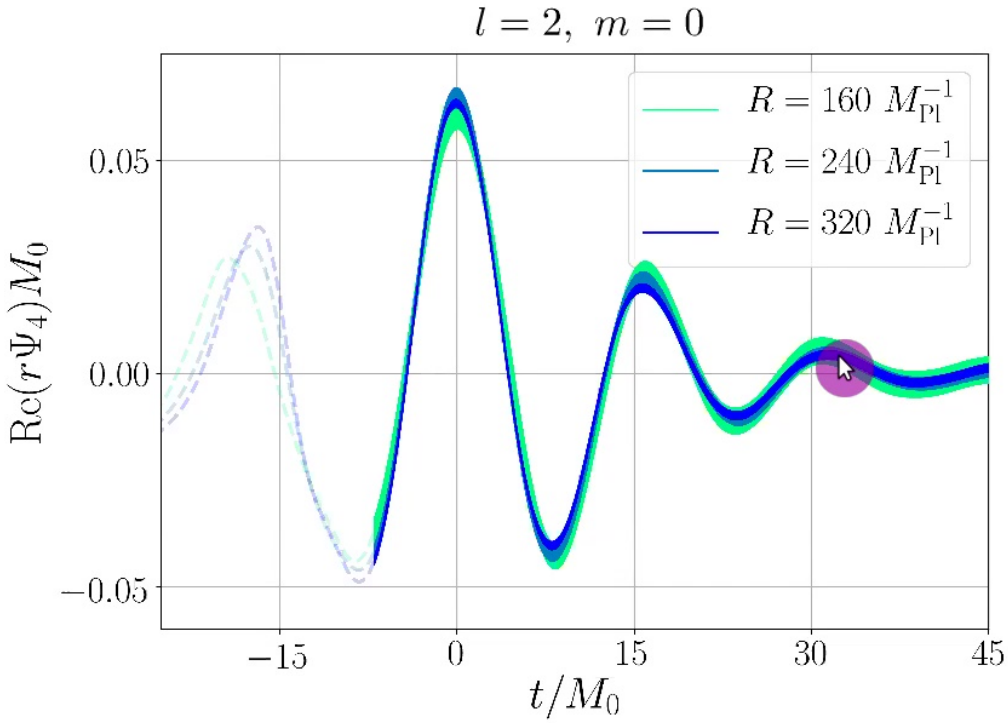


Gravitational Waves

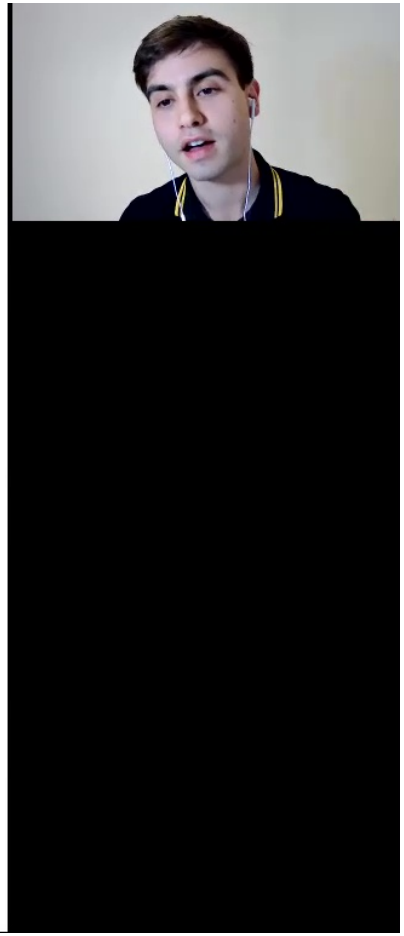
Gravitational Waves



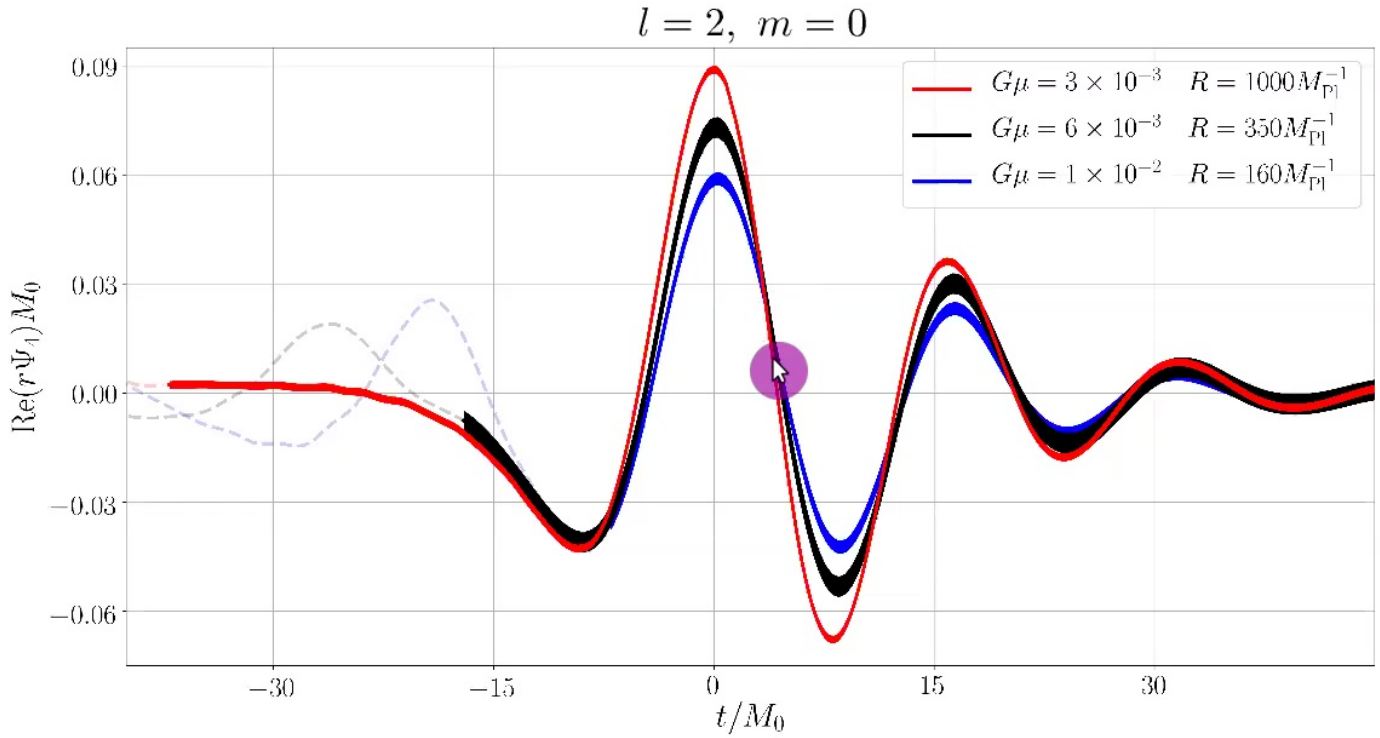
Fixed $G\mu$ Vary string radius R

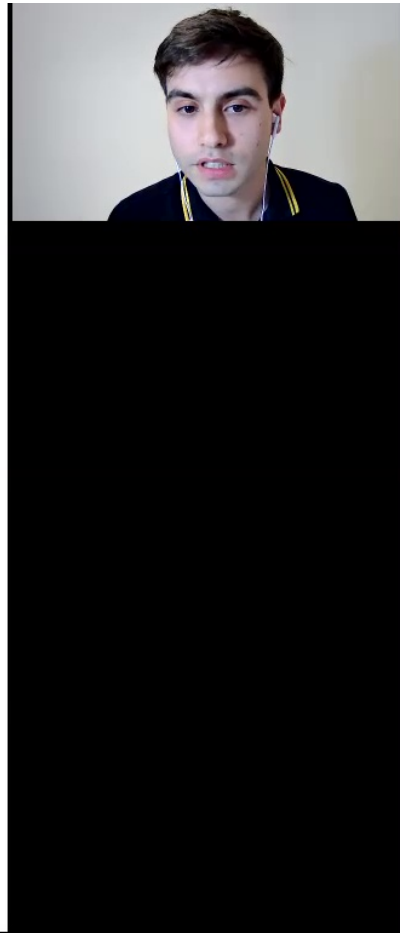


Weakly dependent



Waveform for different $G\mu$ and R





Why?

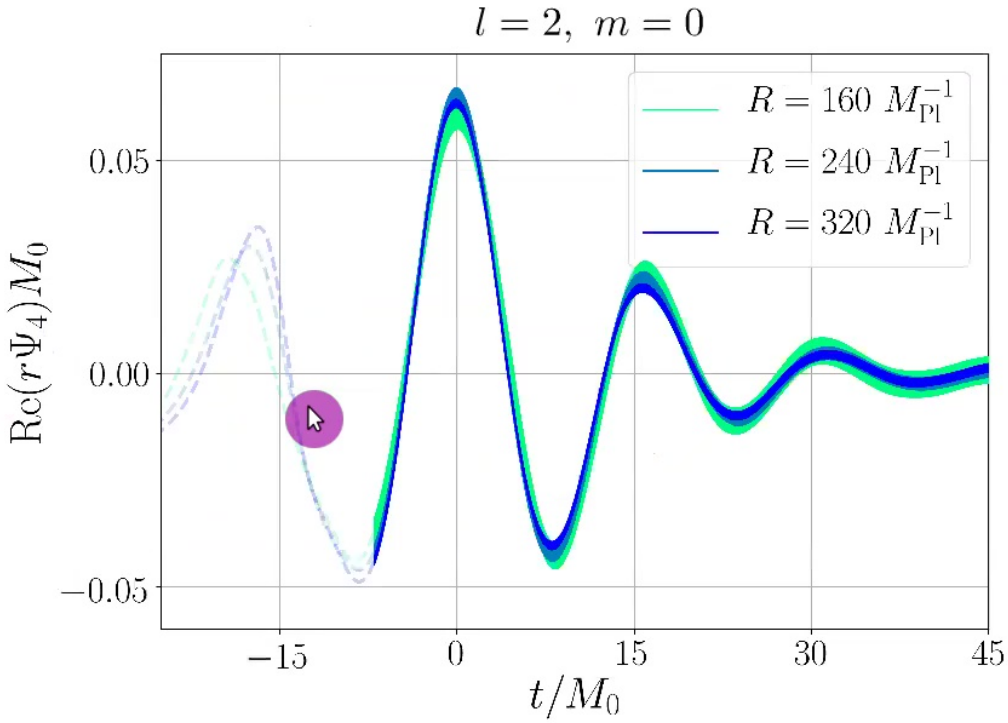
$$r = R\cos\left(\frac{t}{R}\right) \qquad v = \sin\left(\frac{t}{R}\right)$$

Black hole formation when: $r_* = 2GM_0 = 4\pi RG\mu$

$$v_* = \sqrt{1 - 16\pi^2(G\mu)^2} \qquad \gamma_* = \frac{1}{4\pi G\mu}$$

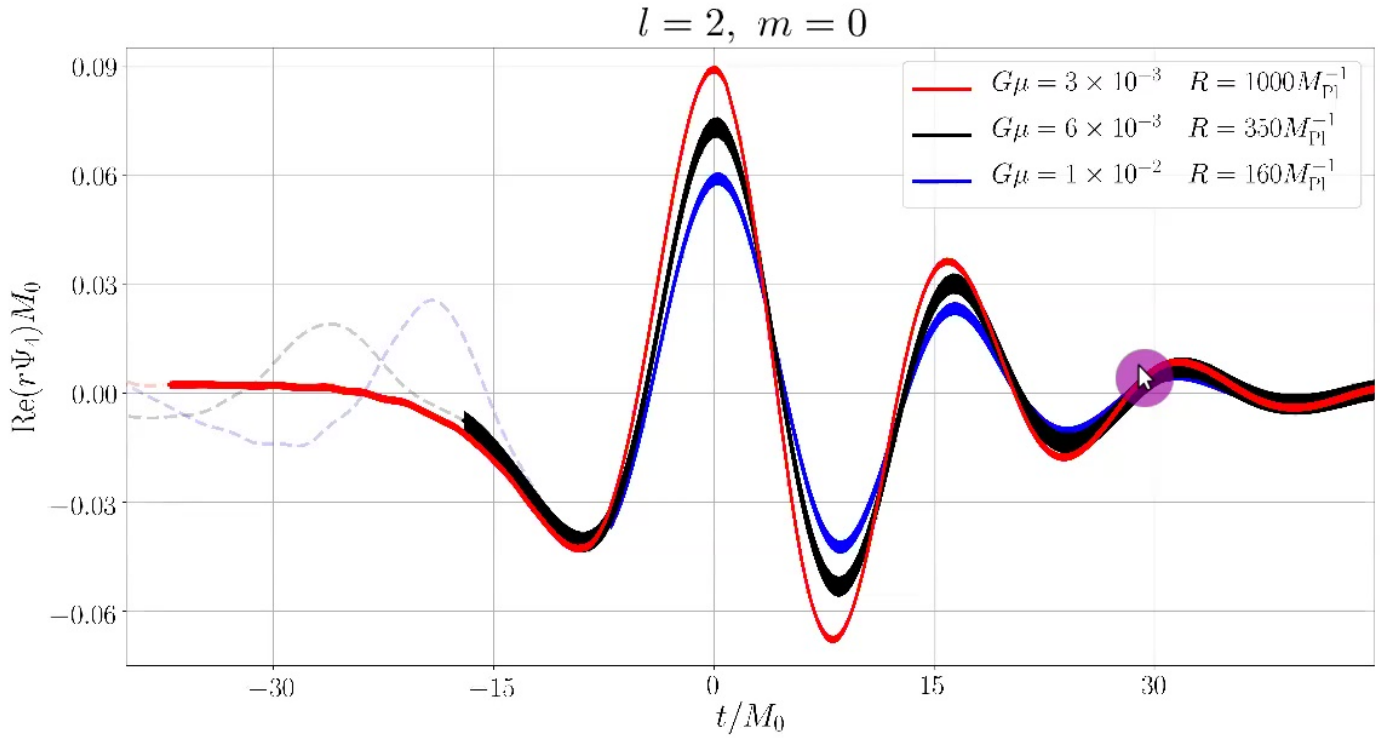
GWs dominated by kinematics

Fixed $G\mu$ Vary string radius R

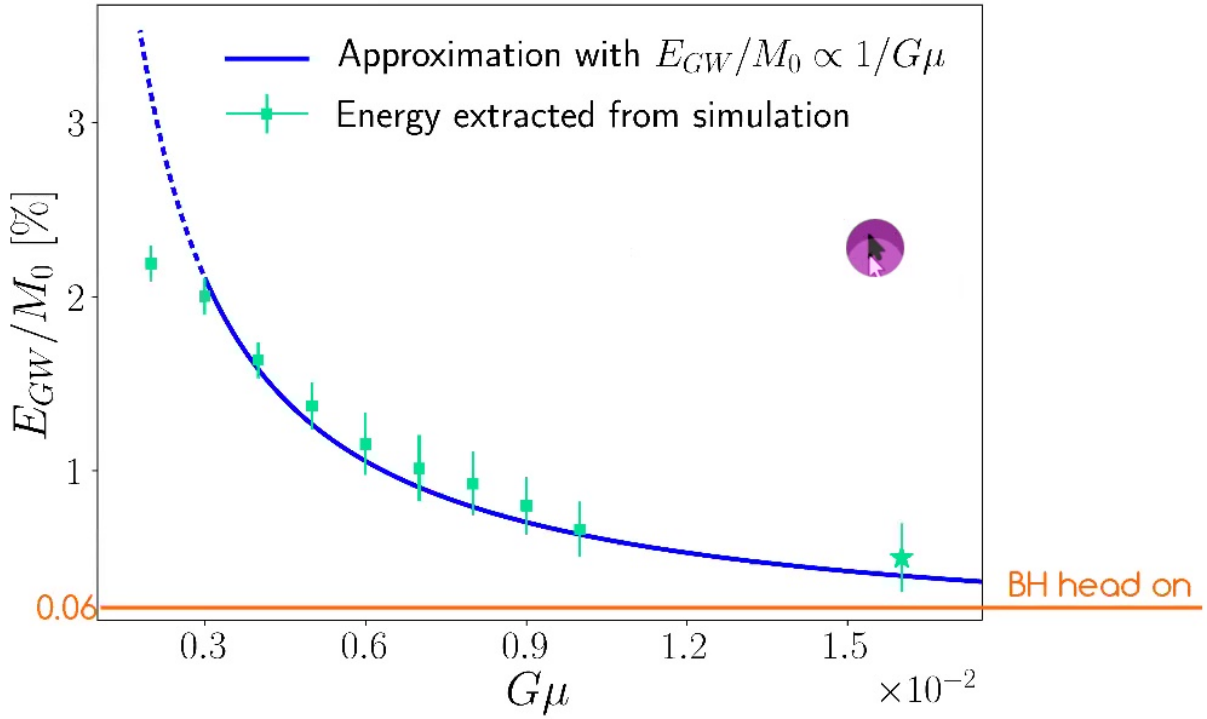


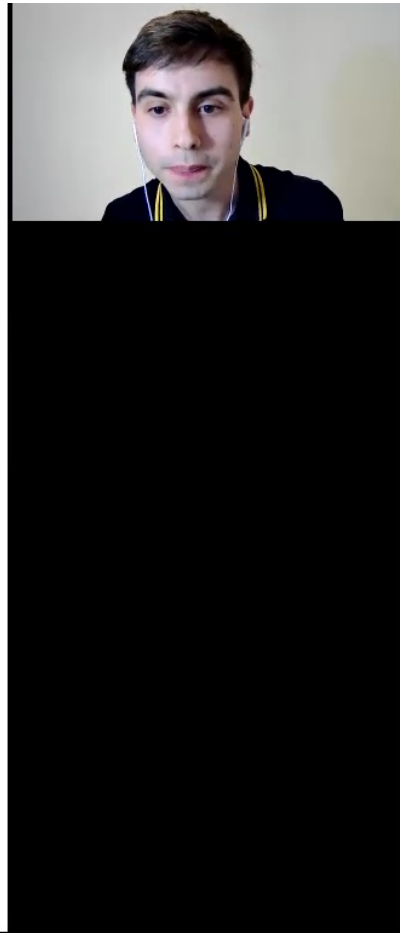
Weakly dependent

Waveform for different $G\mu$ and R



Energy in GWs





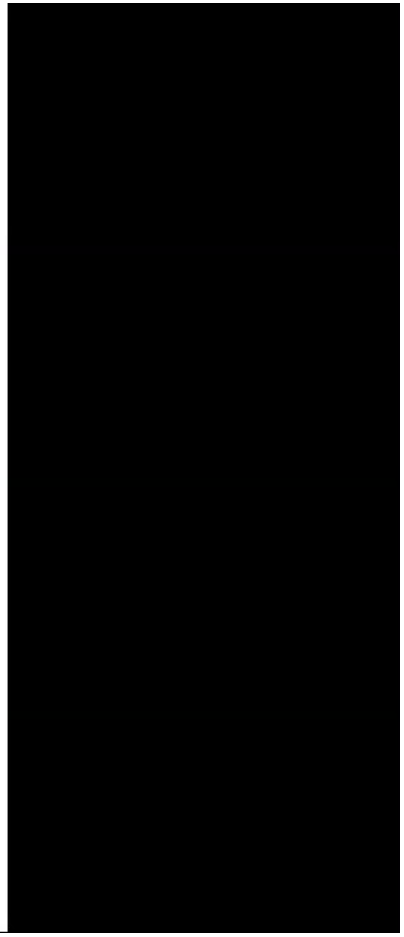
Why?

$$r = R\cos\left(\frac{t}{R}\right) \qquad v = \sin\left(\frac{t}{R}\right)$$

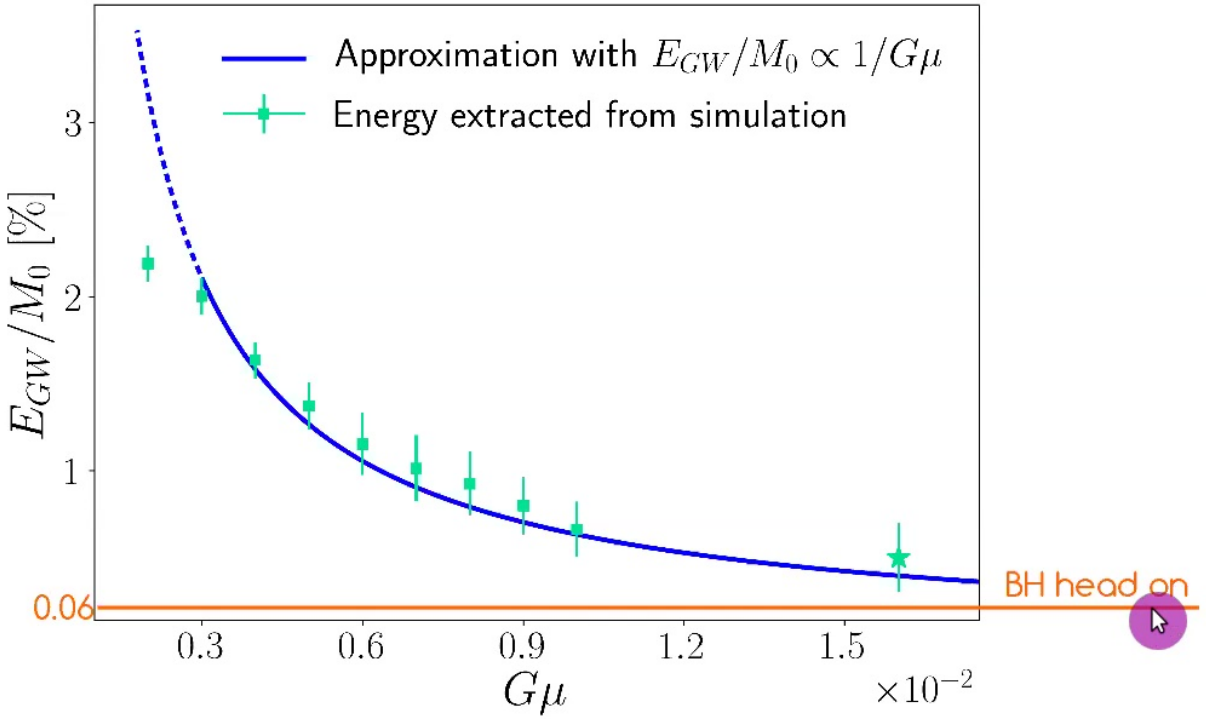
Black hole formation when: $r_* = 2GM_0 = 4\pi RG\mu$

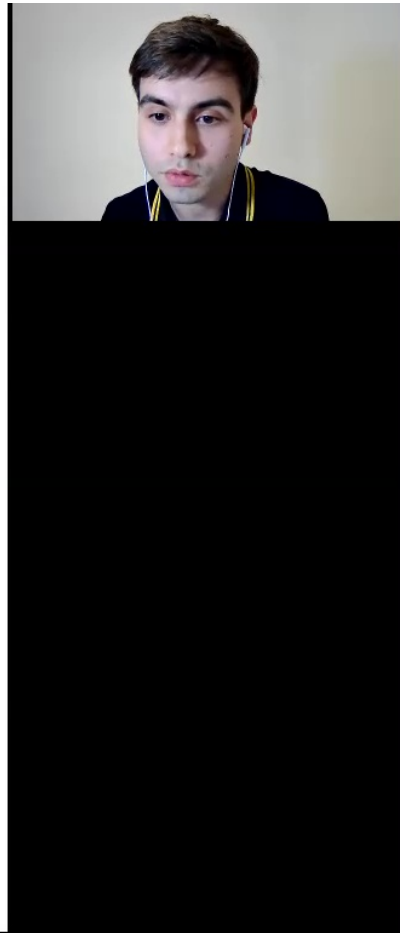
$$v_* = \sqrt{1 - 16\pi^2(G\mu)^2} \qquad \gamma_* = \frac{1}{4\pi G\mu}$$

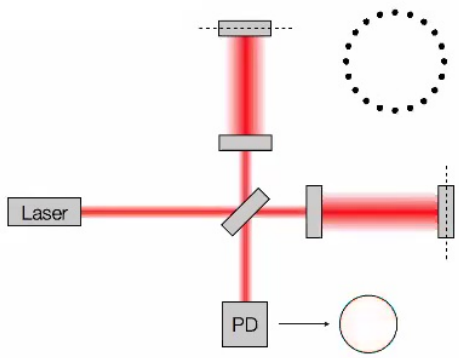
GWs dominated by kinematics



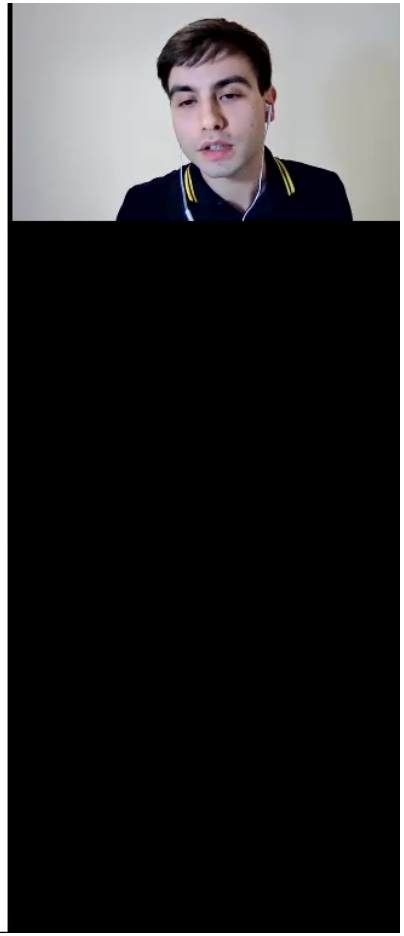
Energy in GWs



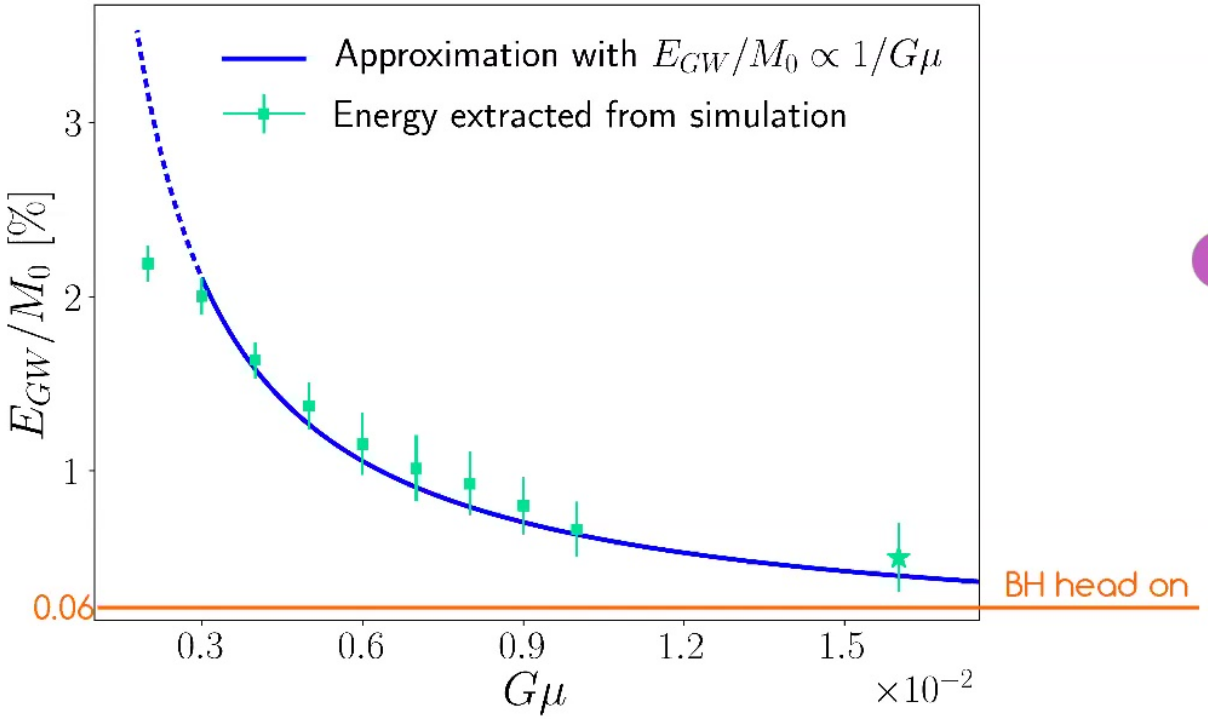




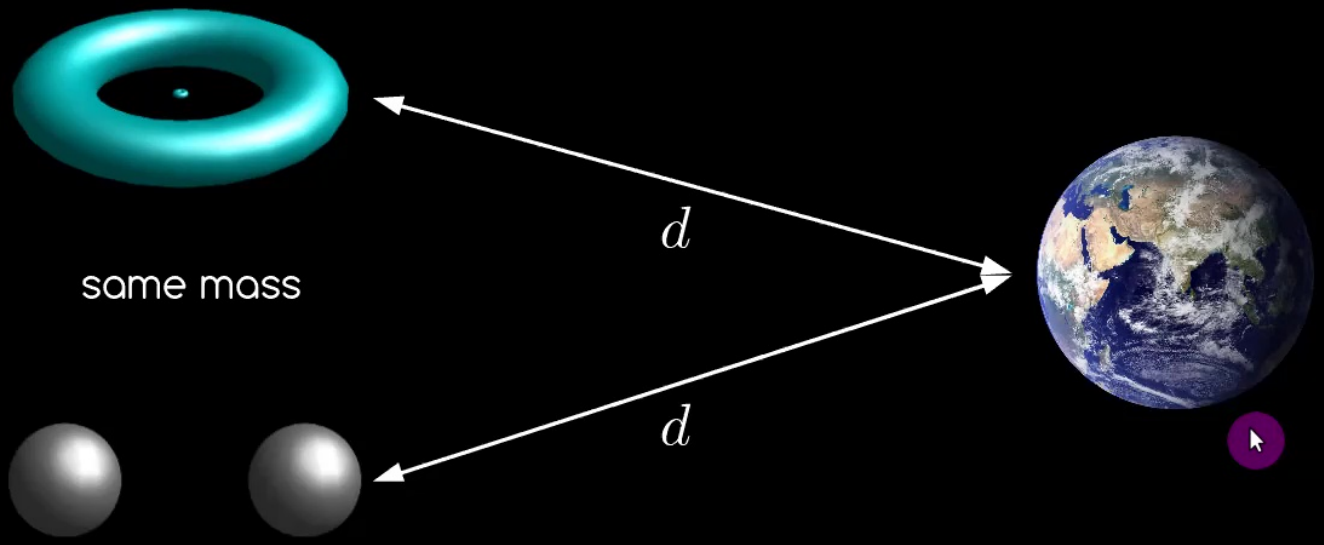
Strain Waveform h_+ $h_\times$



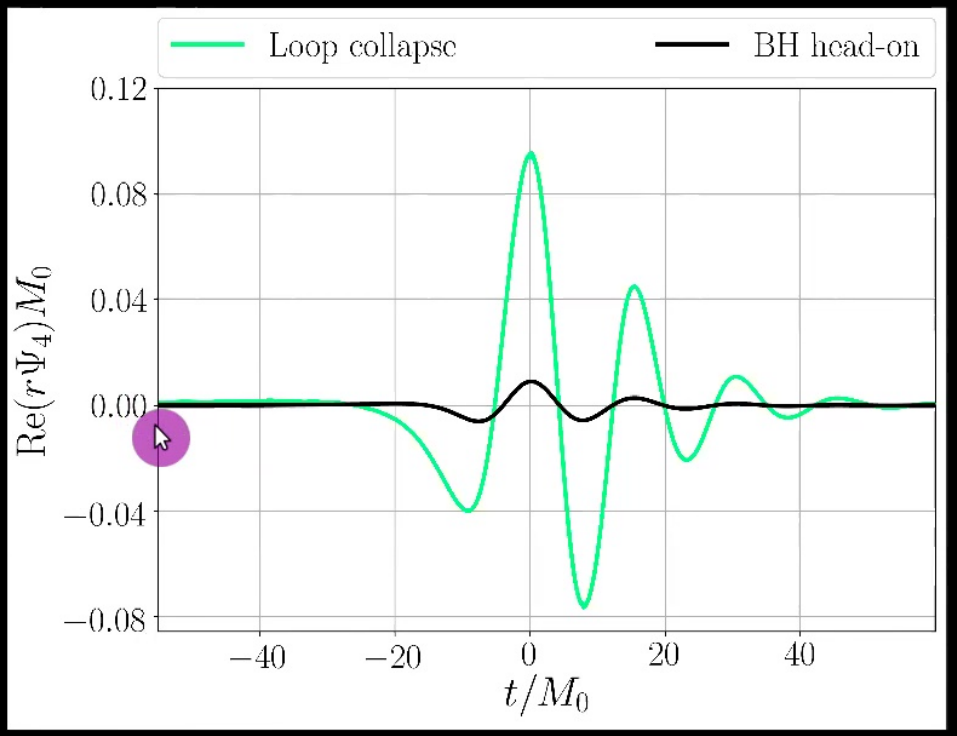
Energy in GWs



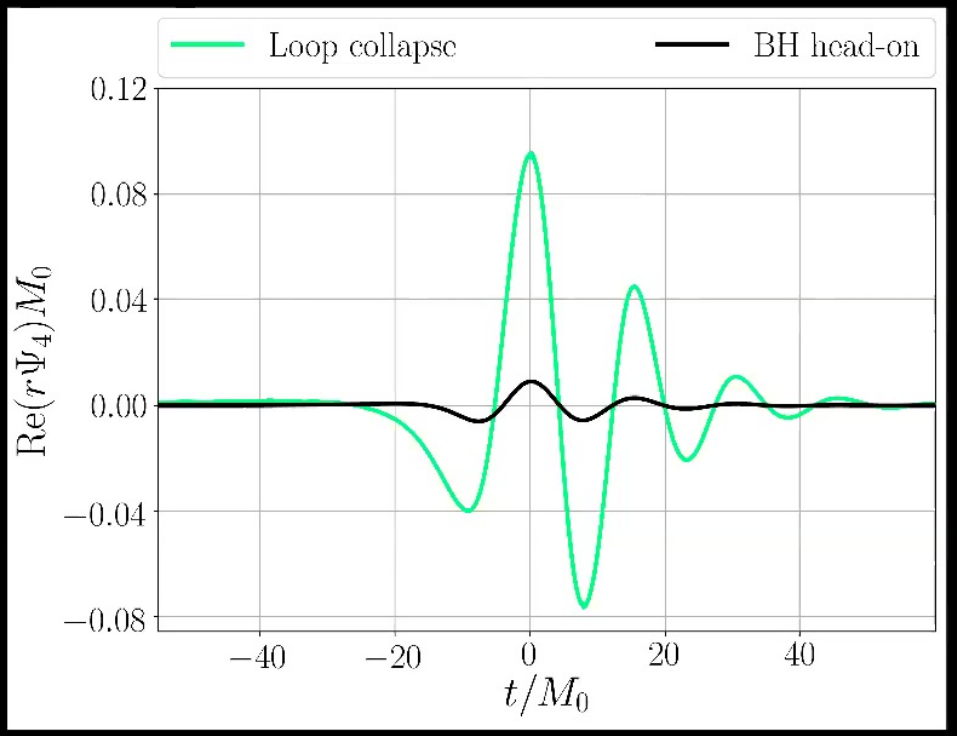
Is it degenerate with BH-BH?



Is it degenerate with BH-BH?



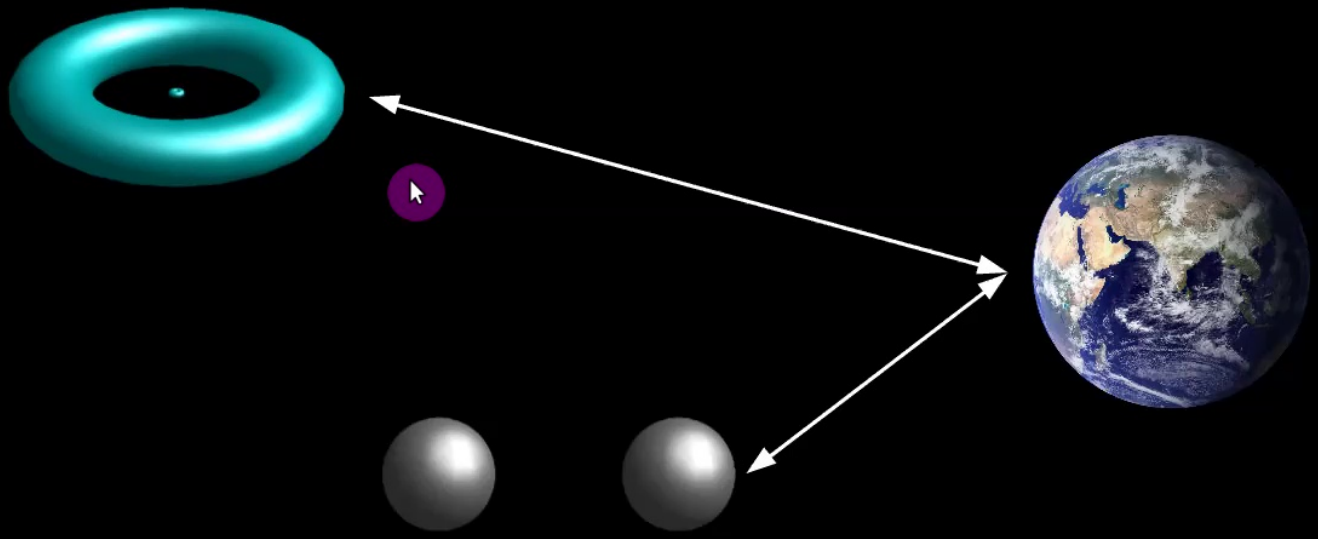
Is it degenerate with BH-BH?



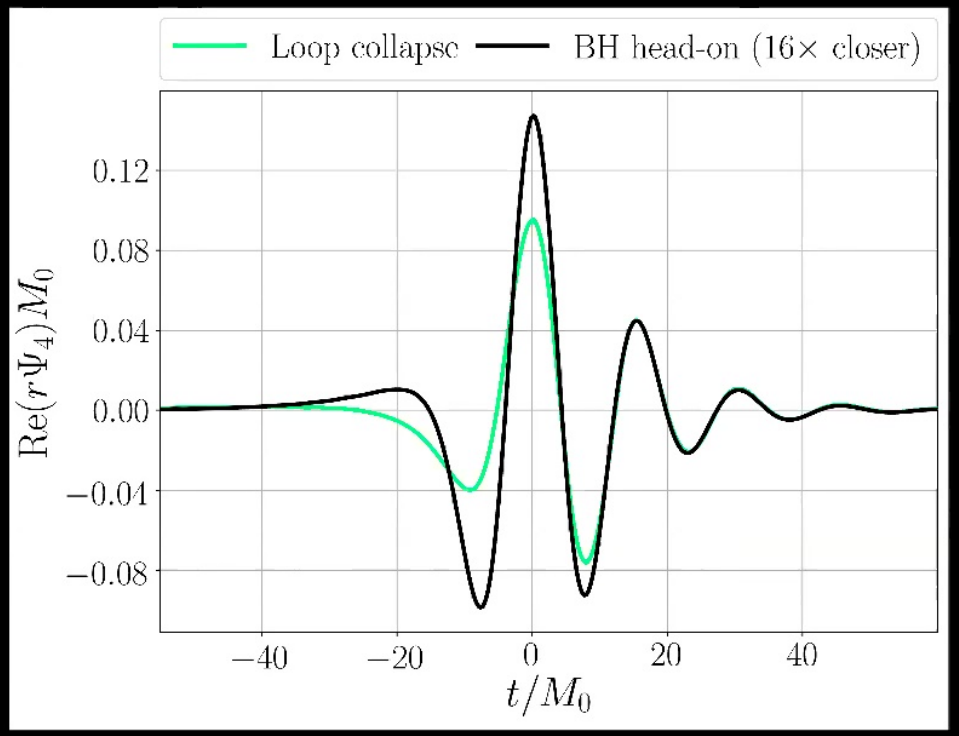
Remember loop collapse is ~30 times more energetic

2% vs 0.06%

Is it degenerate with BH-BH?



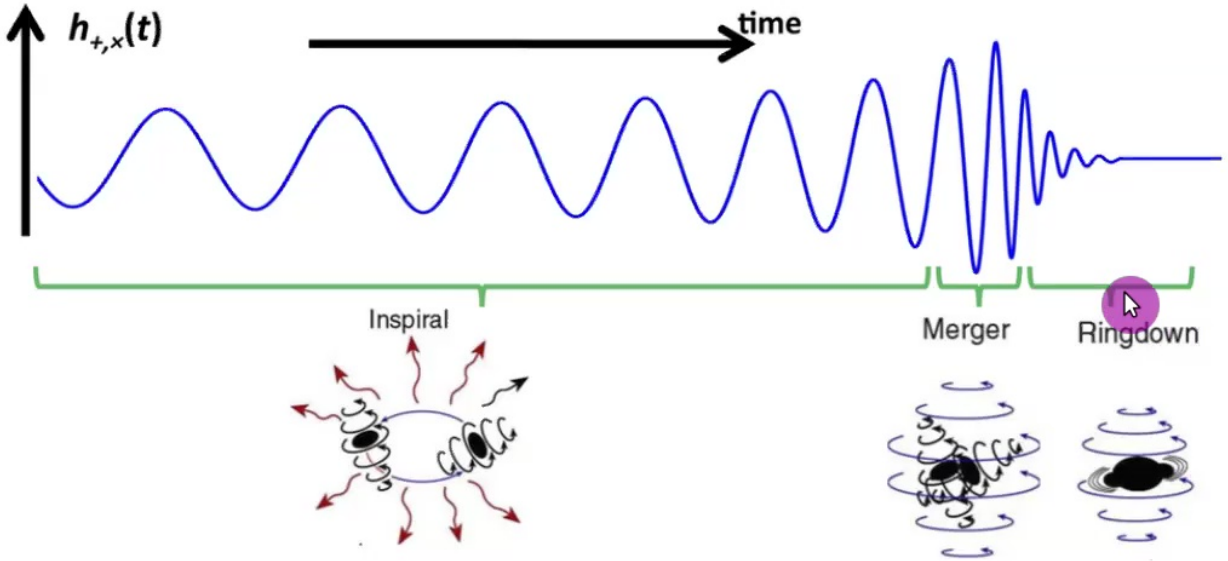
Is it degenerate with BH-BH?



Answer:

NO

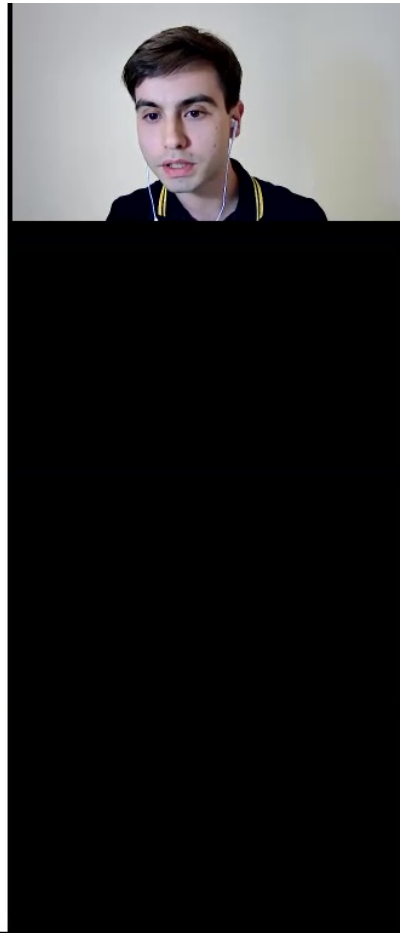
BBH waveform



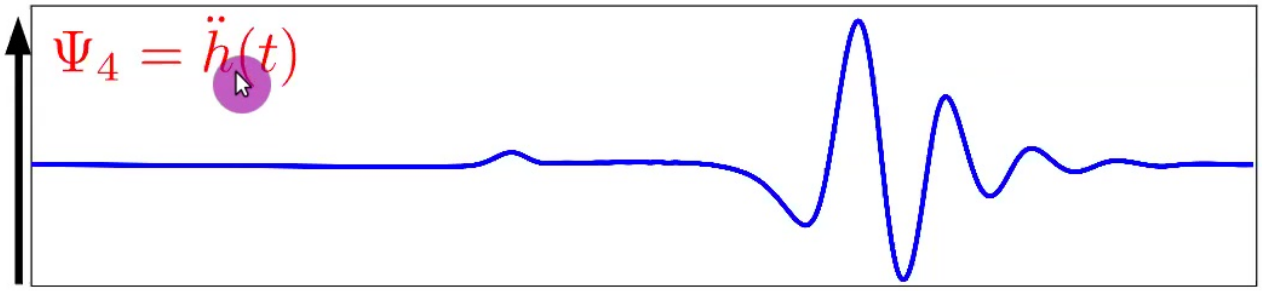
Post-Newtonian techniques

Numerical Relativity

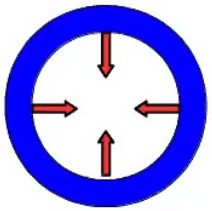
Perturbation theory



String loop waveform



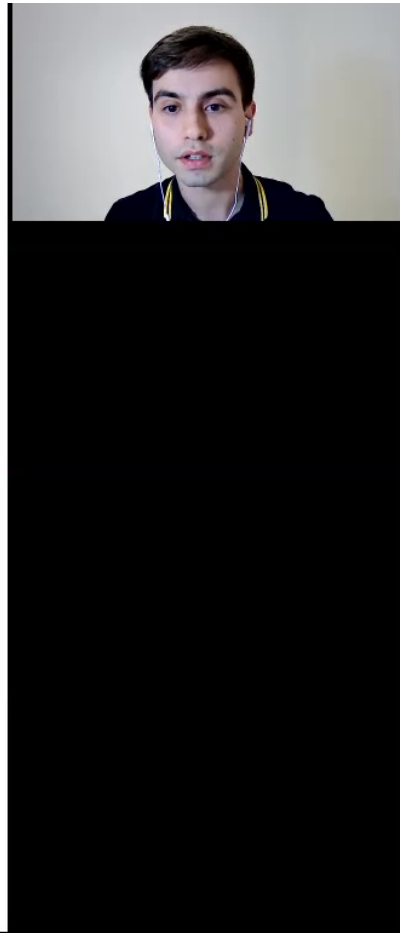
Infall Merger Ringdown



Weak field

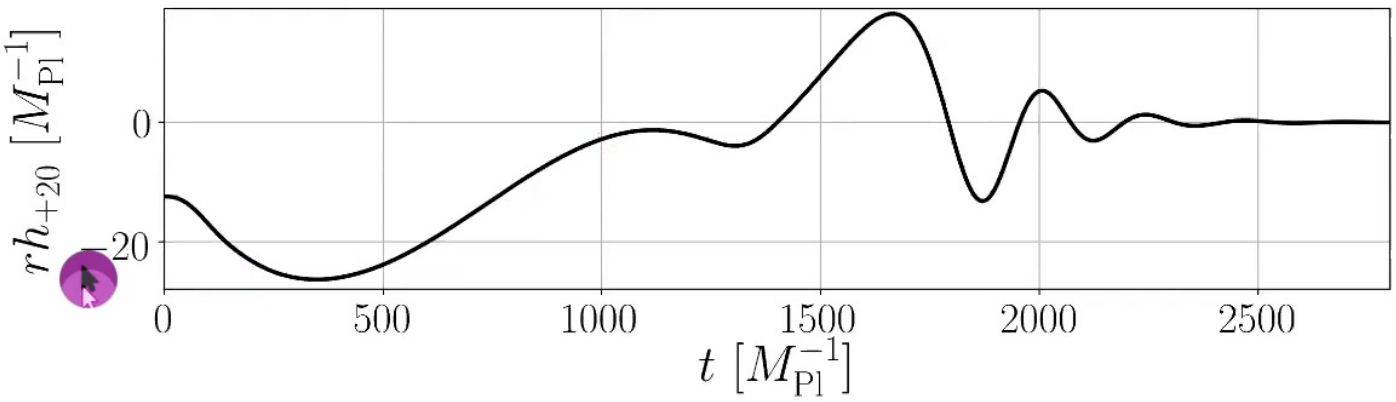
Numerical Relativity

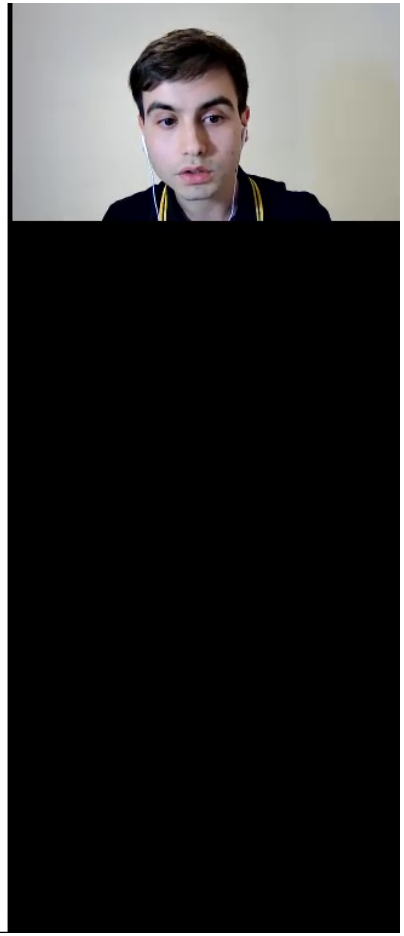
Perturbation theory



Strain waveform

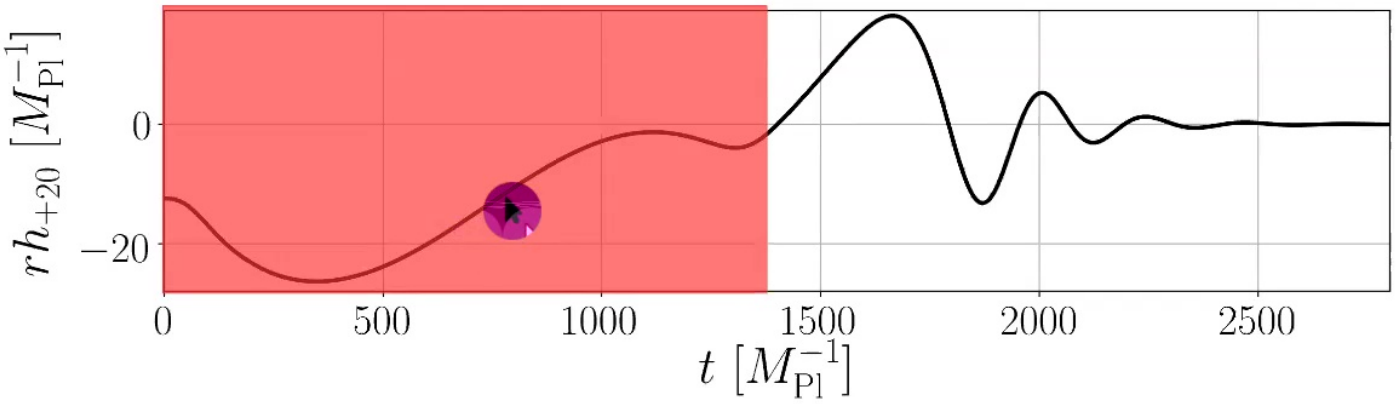
Integrate $\ddot{h}(t) = \Psi_4(t) \longrightarrow h(t) + B$

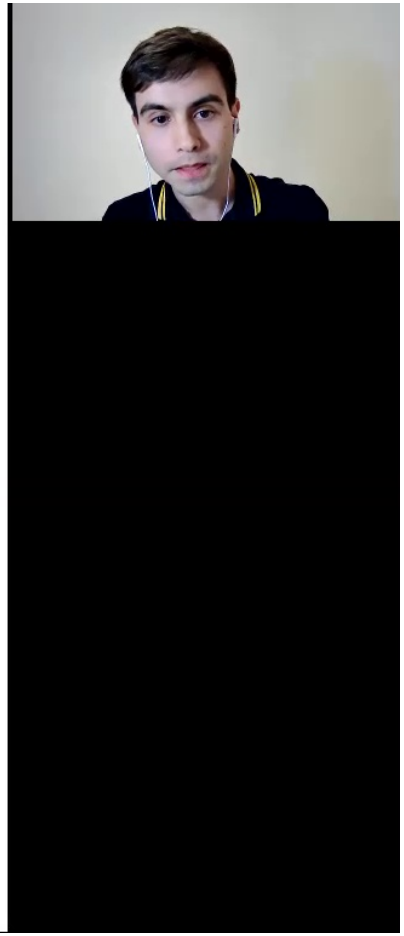




Strain waveform

Integrate $\ddot{h}(t) = \Psi_4(t) \longrightarrow h(t) + B$

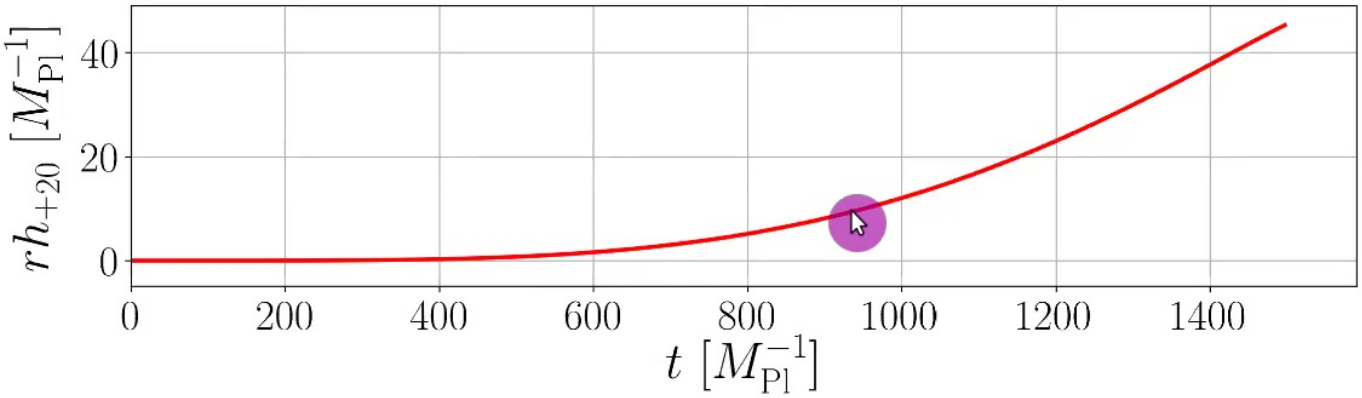




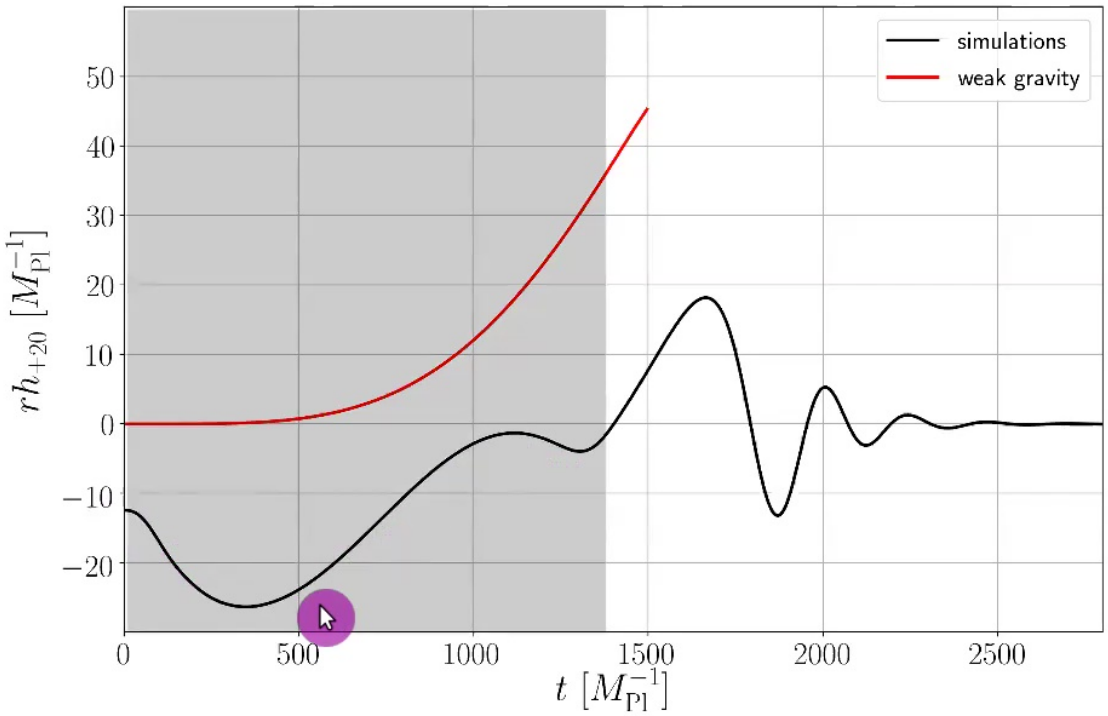
Infall

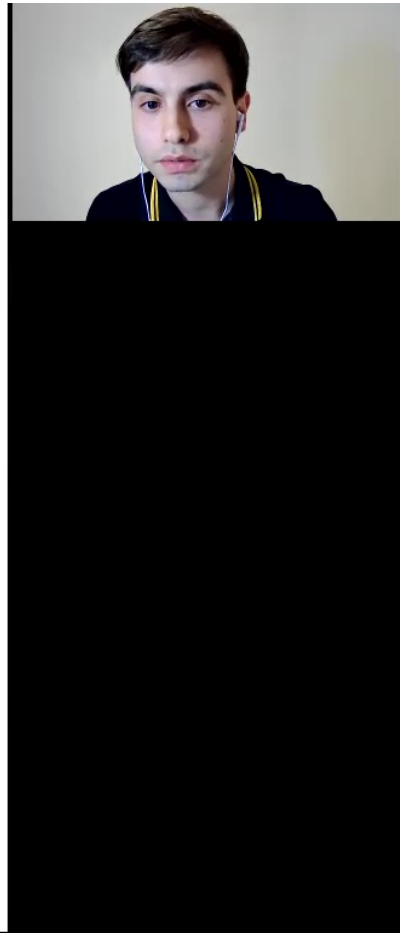
Quadrupole formula only valid at low speeds. Use:

$$rh_{ij}^{TT}(t) = 4G\Lambda_{ij,kl}(\mathbf{n}) \int_{-\infty}^{\infty} d^3x \; T_{kl}\left(t + \mathbf{x}\cdot\mathbf{n}, \mathbf{x}\right)$$

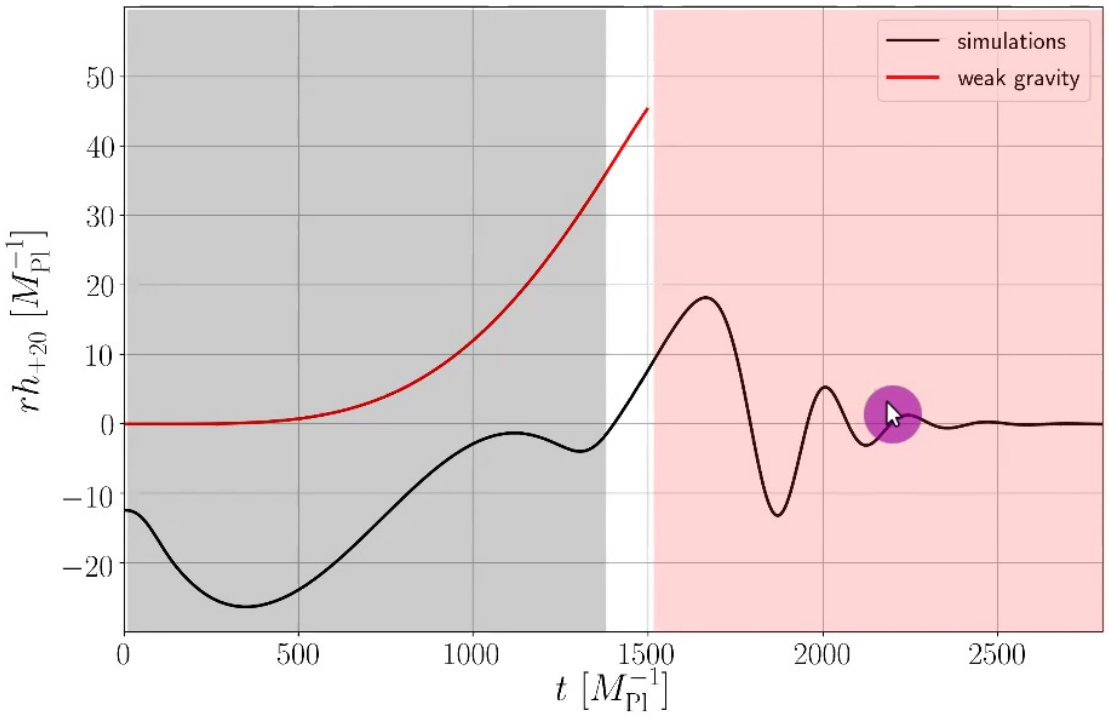


Matching Infall + Merger + Ringdown

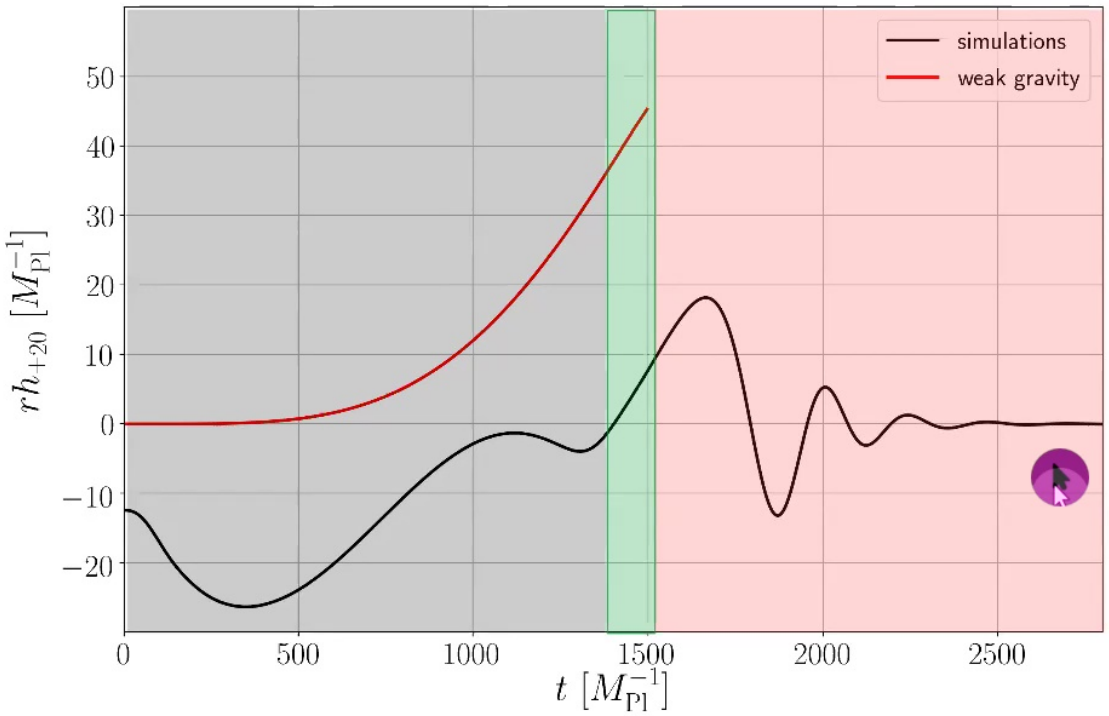




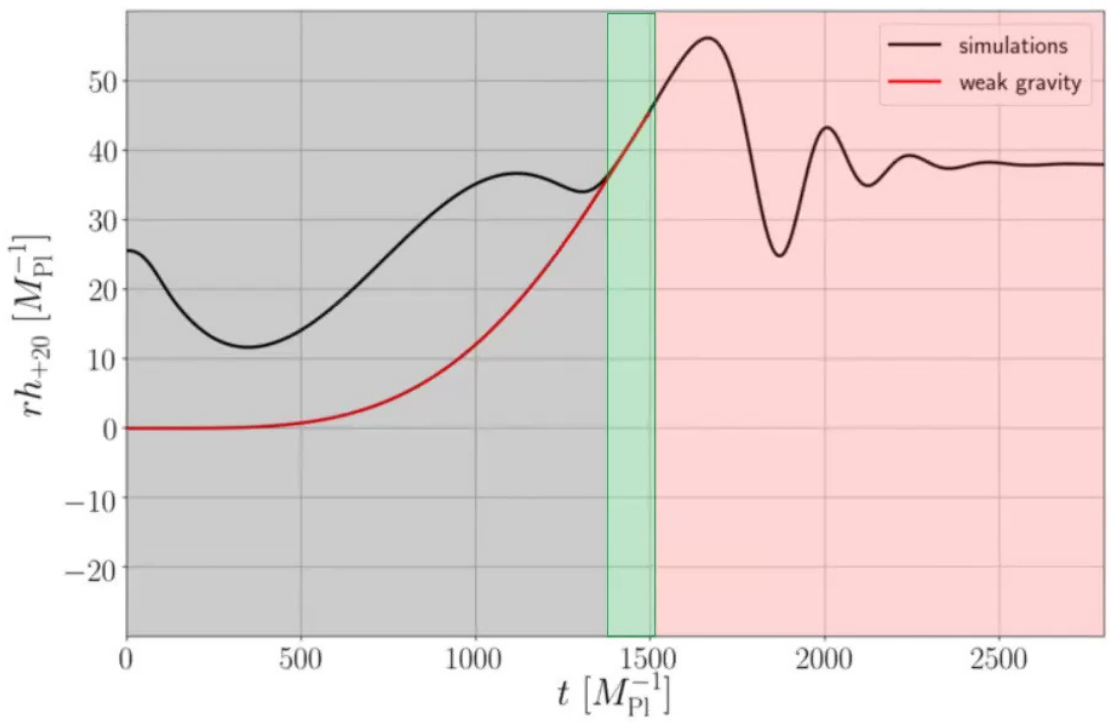
Matching Infall + Merger + Ringdown

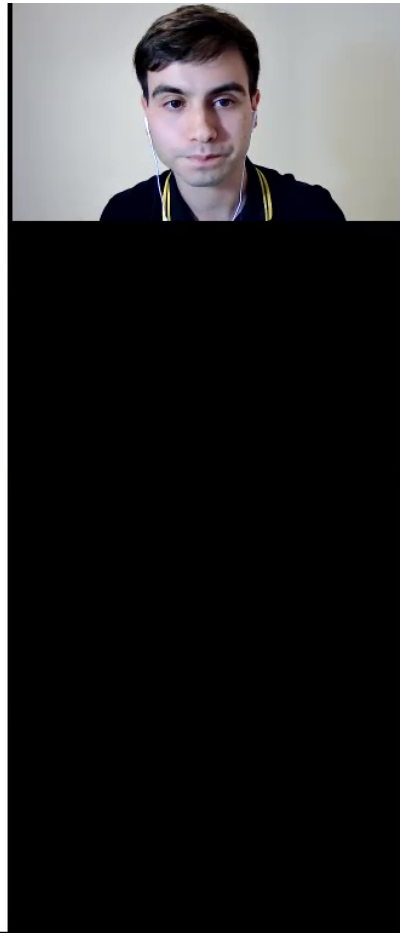


Matching Infall + Merger + Ringdown

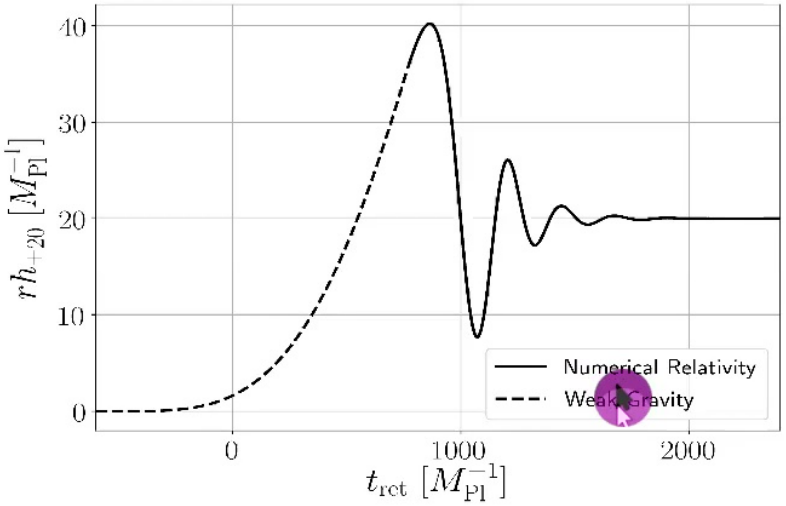


Matching Infall + Merger + Ringdown

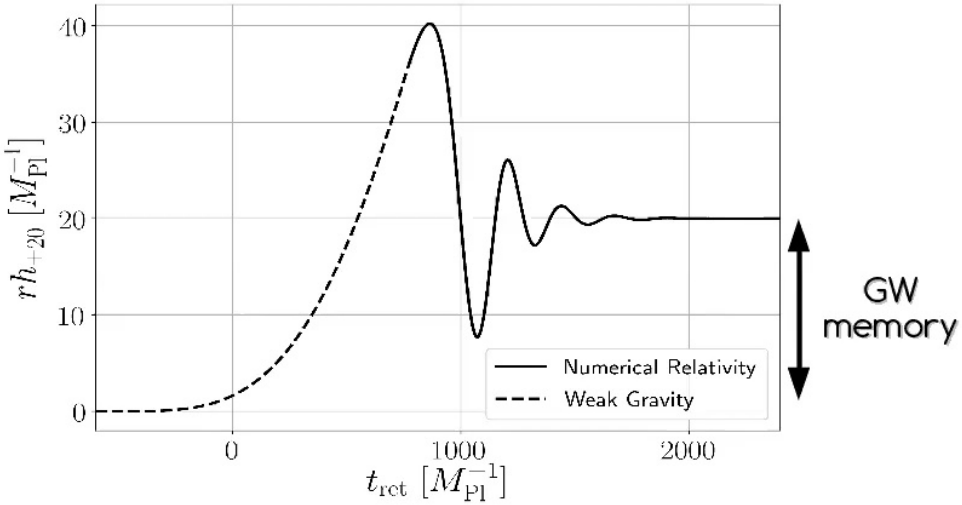




Matching Infall + Merger + Ringdown



Matching Infall + Merger + Ringdown



GW memory

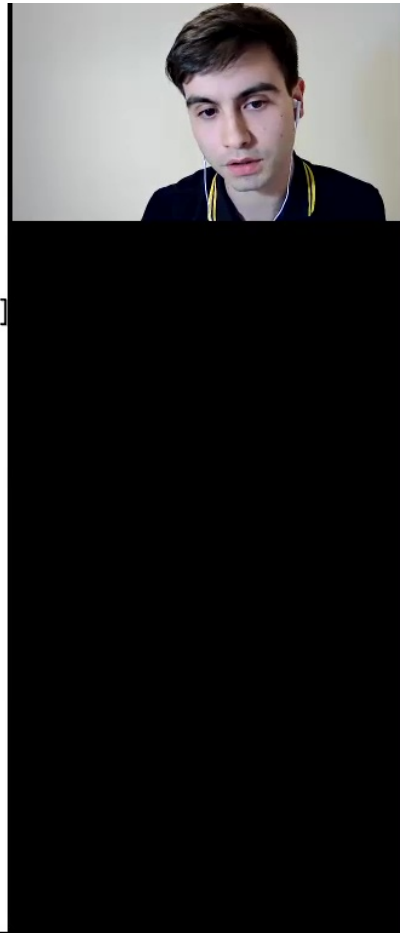
Linear memory

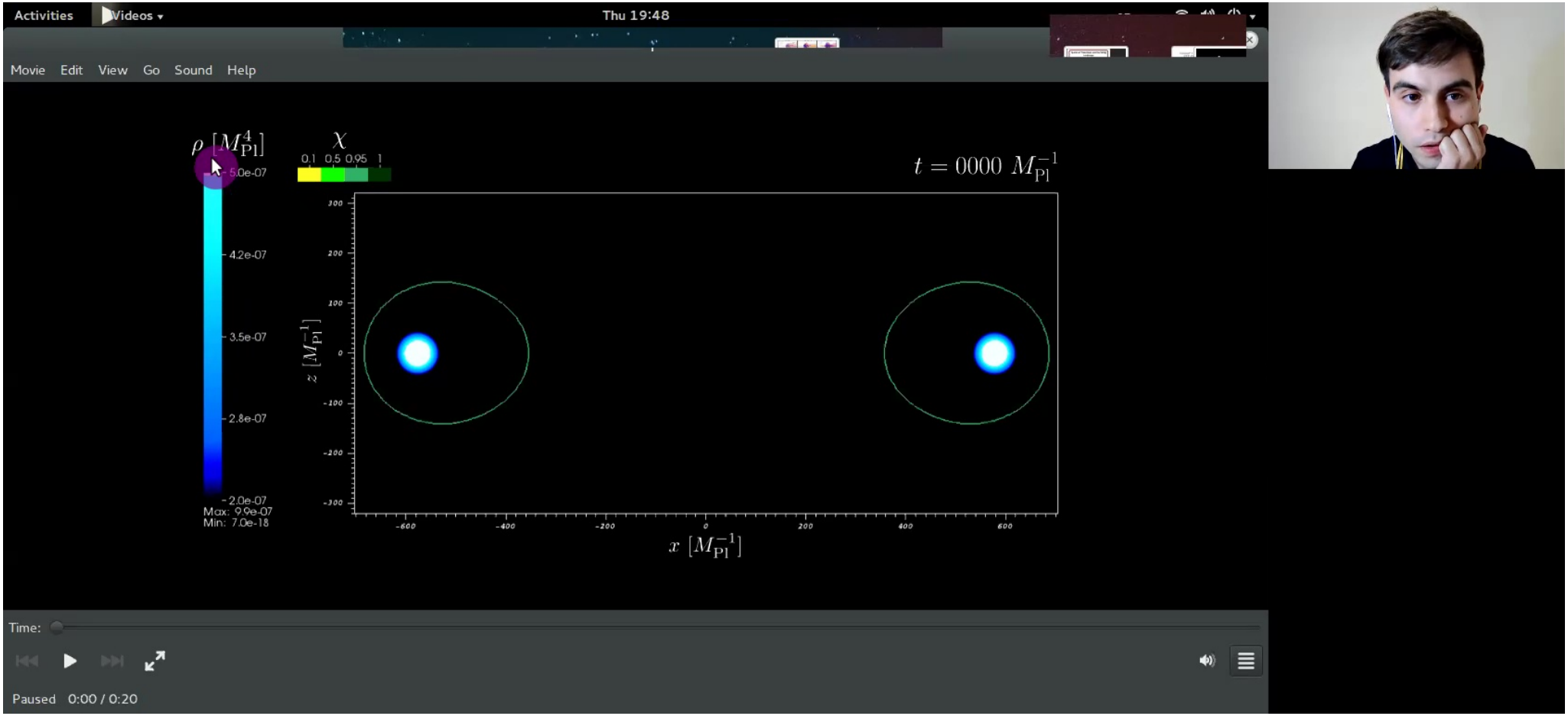
[Zel'Dovich & Polnarev '74; Braginsky & Grishchuk '85; Braginsky & Thorne '87]

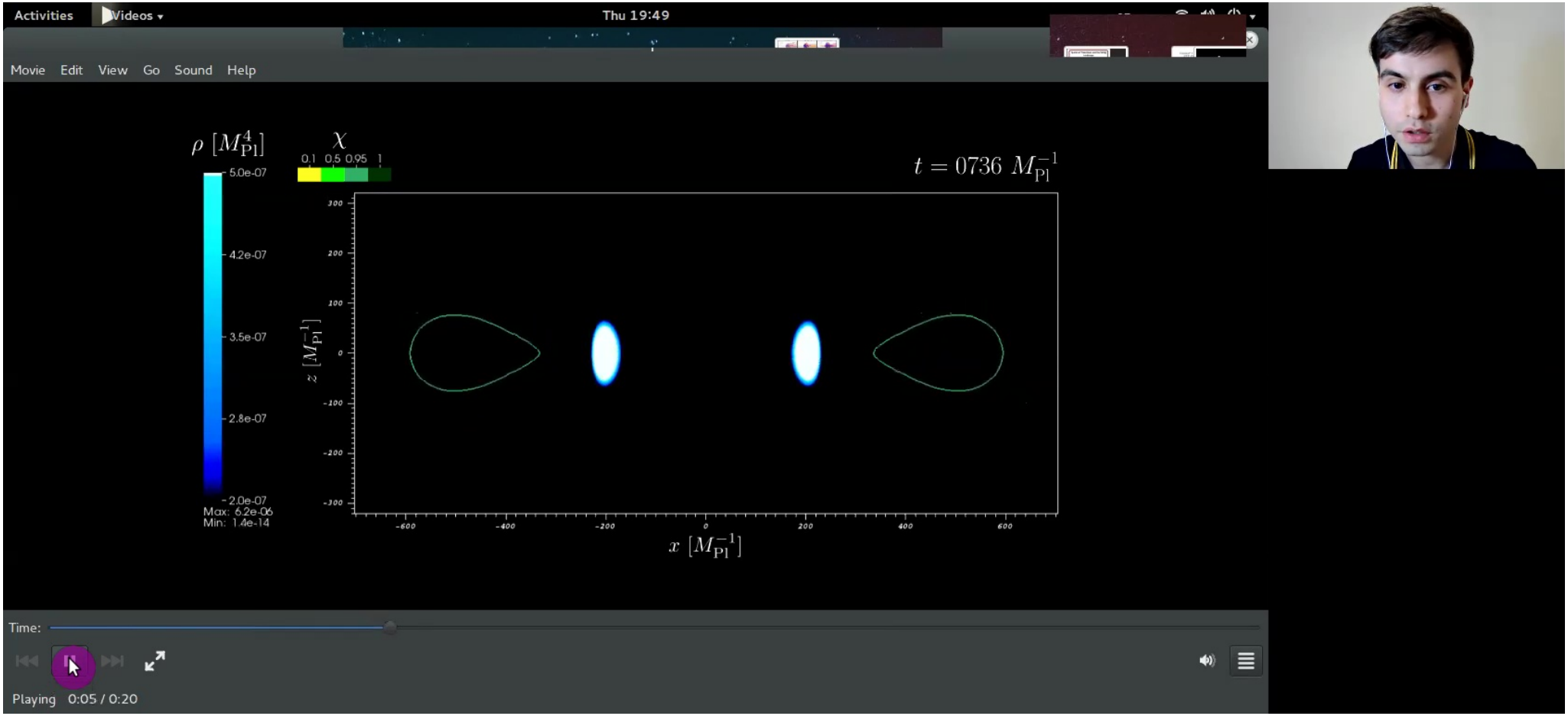
Non-linear memory

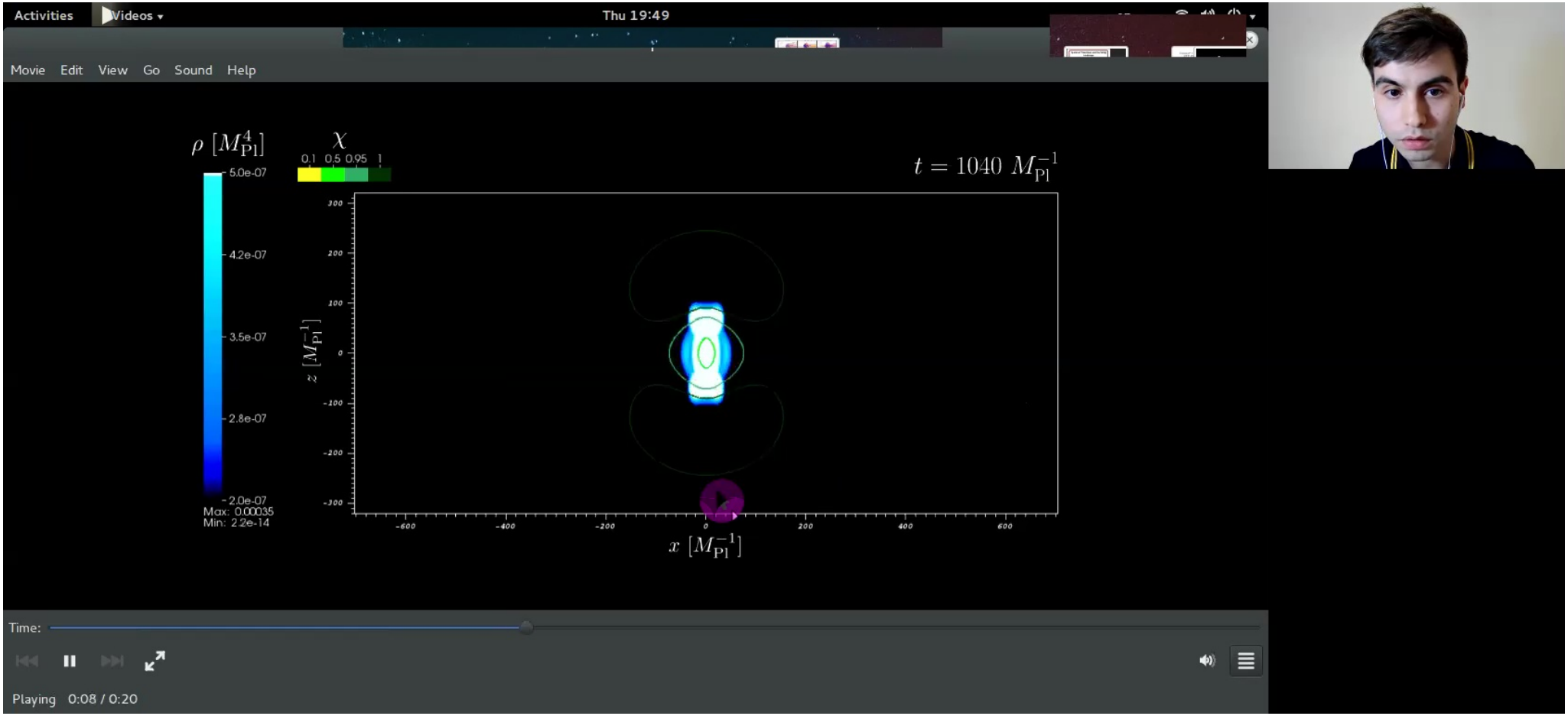
[Christodoulou '91. Thorne '92]

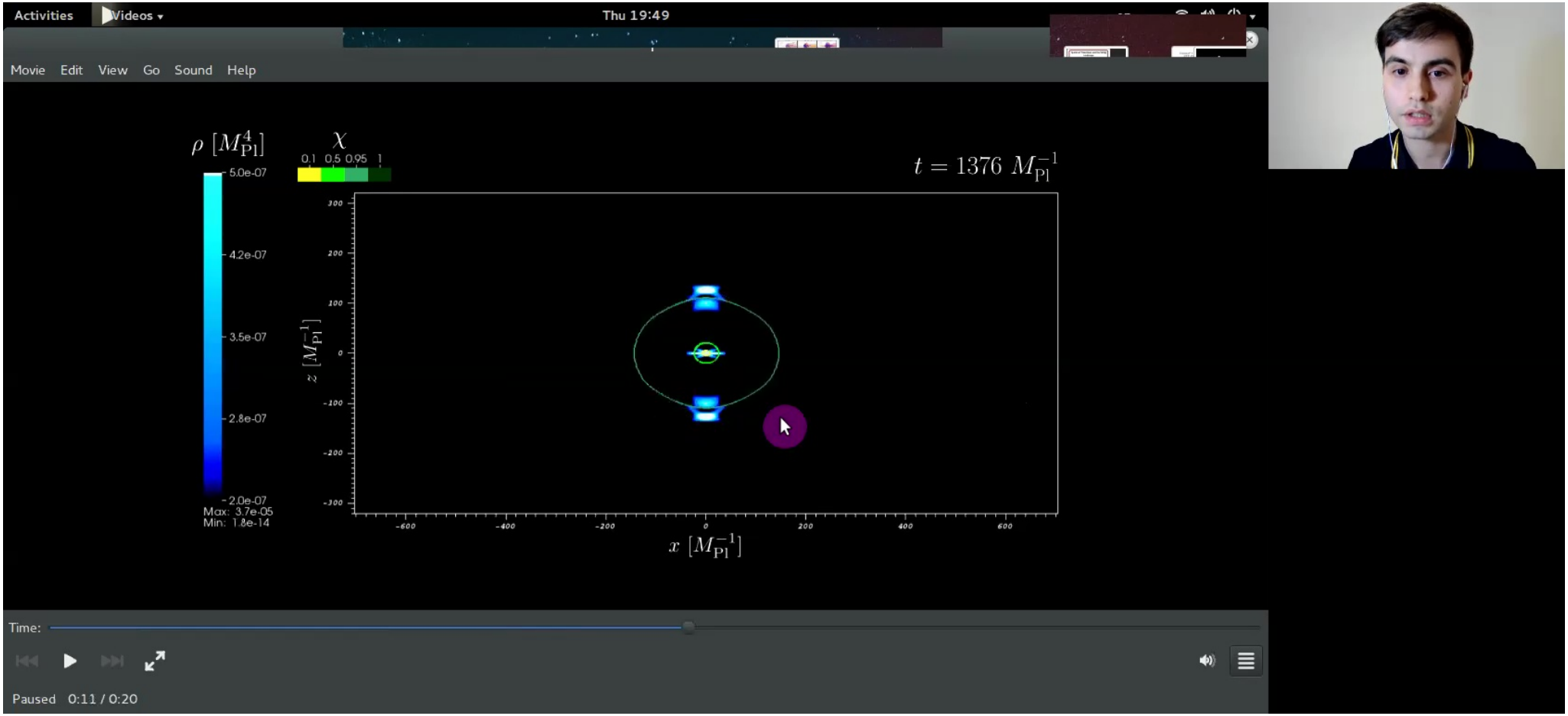
$$\Delta h \propto \left[E_{\rm rad} \left(\frac{v_i v_j}{1 - v cos\theta} \right)^{\rm TT} \right]_{\rm out} - \left[E_{\rm rad} \left(\frac{v_i v_j}{1 - v cos\theta} \right)^{\rm TT} \right]_{\rm in}$$

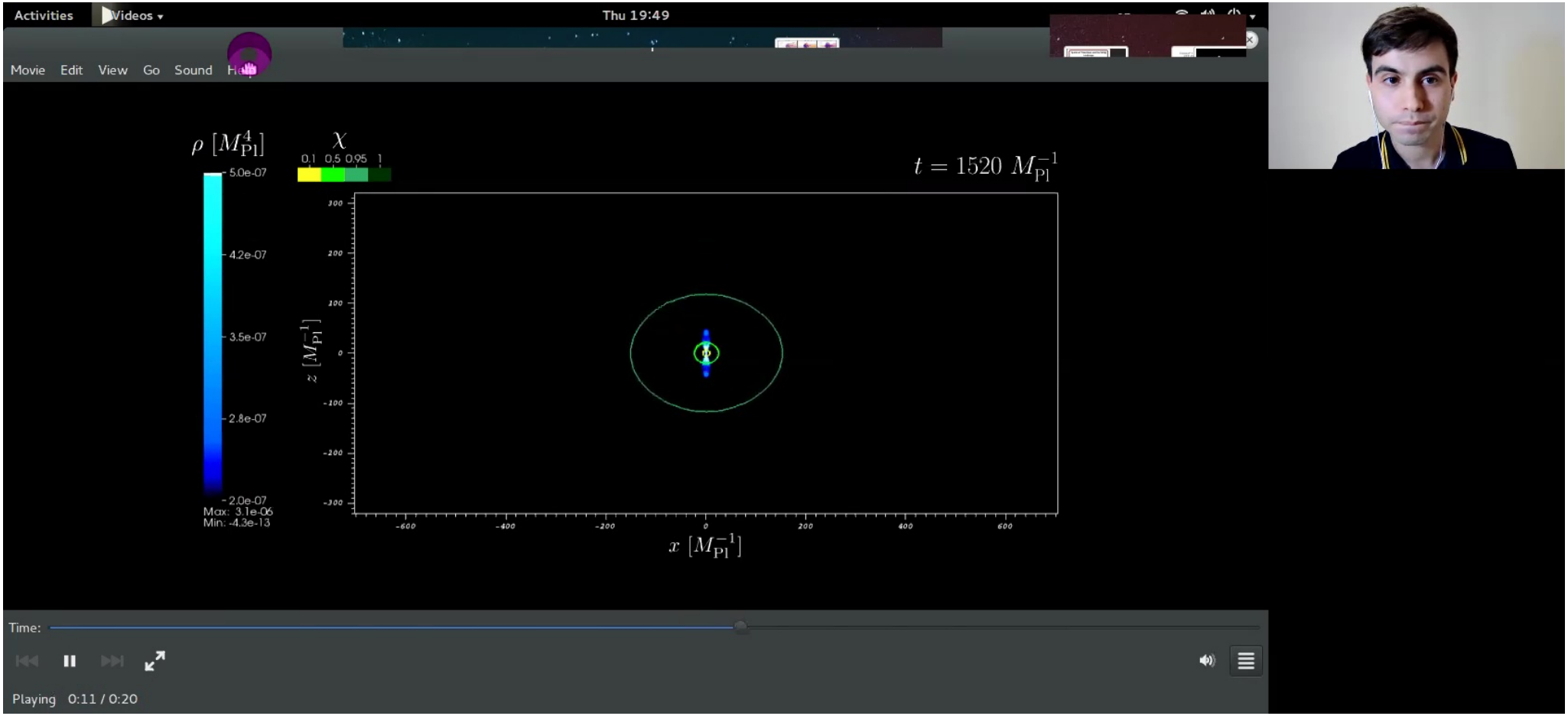



Activities
Videos
Thu 19:48
Movie Edit View Go Sound Help
$\rho\ [M_{\rm Pl}^4]$
5.0e-07
4.2e-07
3.5e-07
2.8e-07
2.0e-07
Max: 9.9e-07
Min: 7.0e-18
χ
0.1 0.5 0.95 1
$t = 0000\ M_{\rm Pl}^{-1}$
$z\ [M_{\rm Pl}^{-1}]$
$x\ [M_{\rm Pl}^{-1}]$
Time:
Paused 0:00 / 0:20

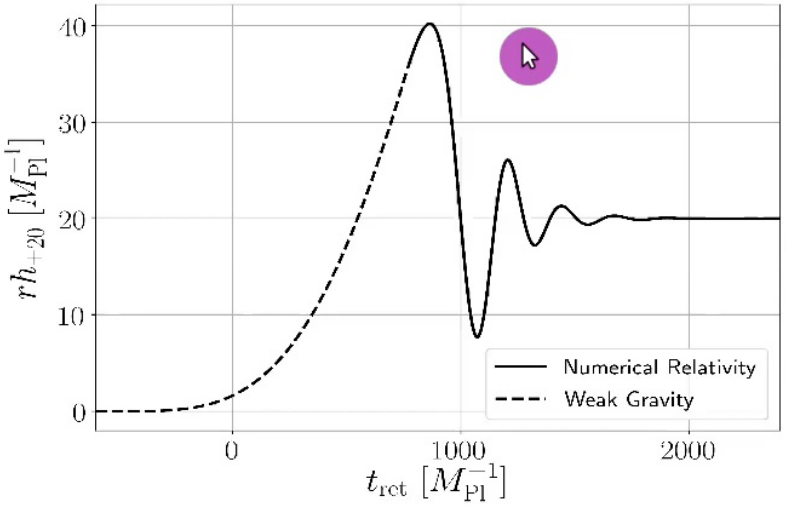

Activities
Videos
Thu 19:49
Movie Edit View Go Sound Help
$\rho\ [M_{\rm Pl}^4]$
5.0e-07
4.2e-07
3.5e-07
2.8e-07
2.0e-07
Max: 6.2e-06
Min: 1.4e-14
χ
0.1 0.5 0.95 1
$t = 0736\ M_{\rm Pl}^{-1}$
$z\ [M_{\rm Pl}^{-1}]$
$x\ [M_{\rm Pl}^{-1}]$
Time:
Playing 0:05 / 0:20


Activities
Videos
Thu 19:49
Movie Edit View Go Sound Help
$\rho\ [M_{\rm Pl}^4]$
5.0e-07
4.2e-07
3.5e-07
2.8e-07
2.0e-07
Max: 0.00035
Min: 2.2e-14
χ
0.1 0.5 0.95 1
$t = 1040\ M_{\rm Pl}^{-1}$
$z\ [M_{\rm Pl}^{-1}]$
$x\ [M_{\rm Pl}^{-1}]$
Time:
Playing 0:08 / 0:20


Activities
Videos
Thu 19:49
Movie Edit View Go Sound Help
$\rho\ [M_{\rm Pl}^4]$
5.0e-07
4.2e-07
3.5e-07
2.8e-07
2.0e-07
Max: 3.7e-05
Min: 1.8e-14
χ
0.1 0.5 0.95 1
$t = 1376\ M_{\rm Pl}^{-1}$
$z\ [M_{\rm Pl}^{-1}]$
$x\ [M_{\rm Pl}^{-1}]$
Time:
Paused 0:11 / 0:20


Activities
Videos
Thu 19:49
Movie Edit View Go Sound
$\rho\ [M_{\rm Pl}^4]$
5.0e-07
4.2e-07
3.5e-07
2.8e-07
2.0e-07
Max: 3.1e-06
Min: -4.3e-13
χ
0.1 0.5 0.95 1
$t = 1520\ M_{\rm Pl}^{-1}$
$z\ [M_{\rm Pl}^{-1}]$
$x\ [M_{\rm Pl}^{-1}]$
Time:
Playing 0:11 / 0:20

Matching Infall + Merger + Ringdown



GW memory

Linear memory

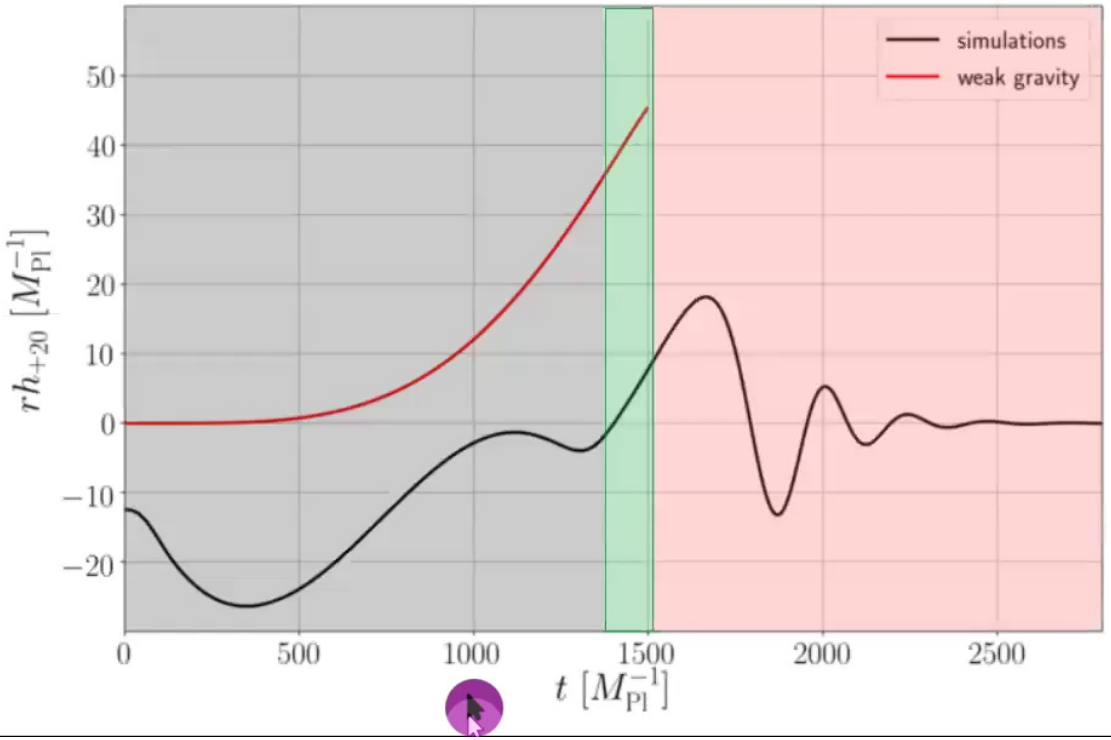
[Zel'Dovich & Polnarev '74; Braginsky & Grishchuk '85; Braginsky & Thorne '87]

Non-linear memory

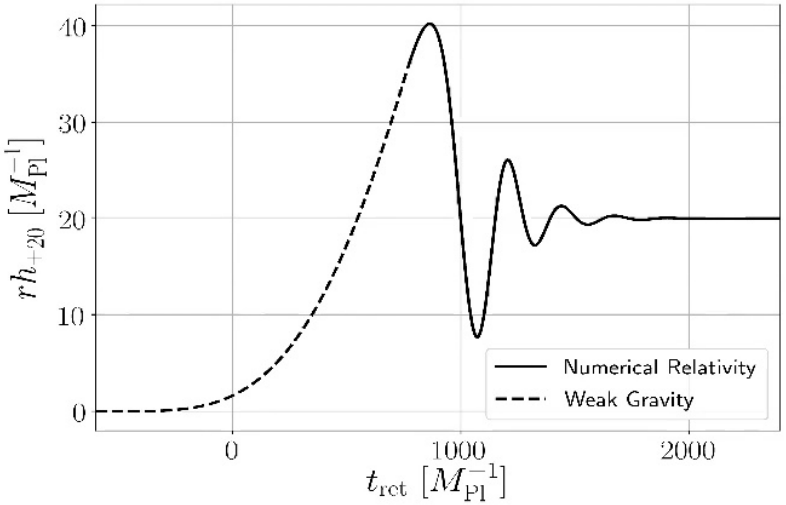
[Christodoulou '91. Thorne '92]

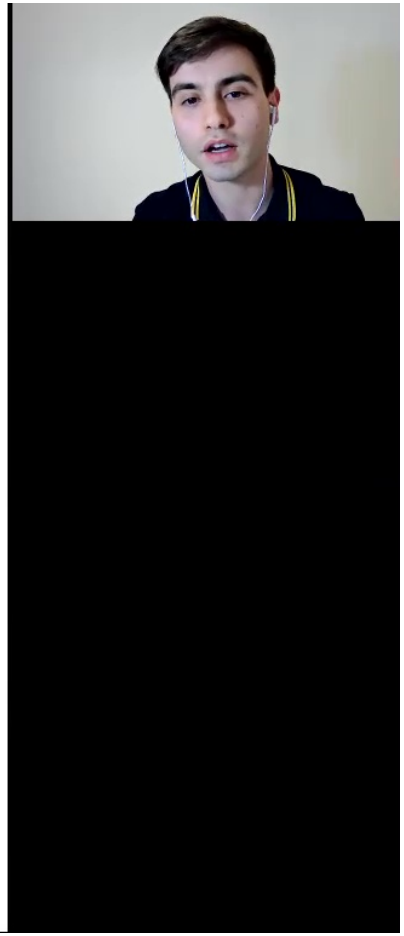
$$\Delta h \propto \left[E_{\rm rad}\left(\frac{v_i v_j}{1-v cos\theta}\right)^{\rm TT}\right]_{\rm out} - \left[E_{\rm rad}\left(\frac{v_i v_j}{1-v cos\theta}\right)^{\rm TT}\right]_{\rm in}$$

Matching Infall + Merger + Ringdown

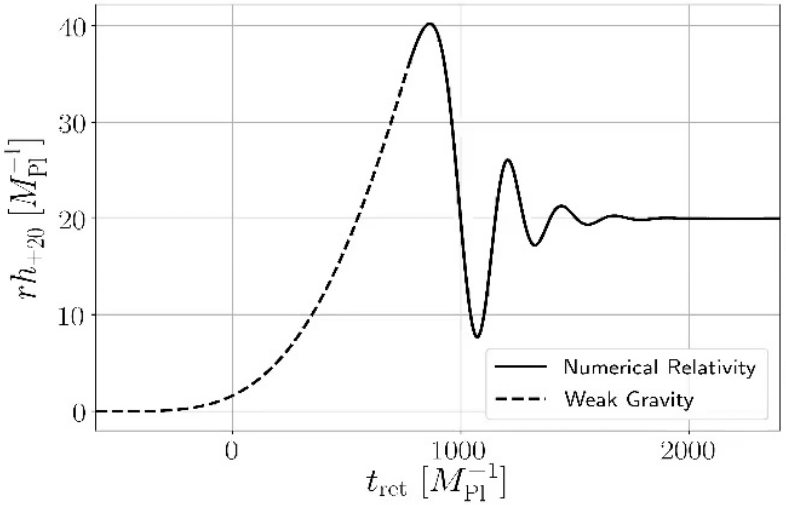


Matching Infall + Merger + Ringdown





Matching Infall + Merger + Ringdown



GW memory

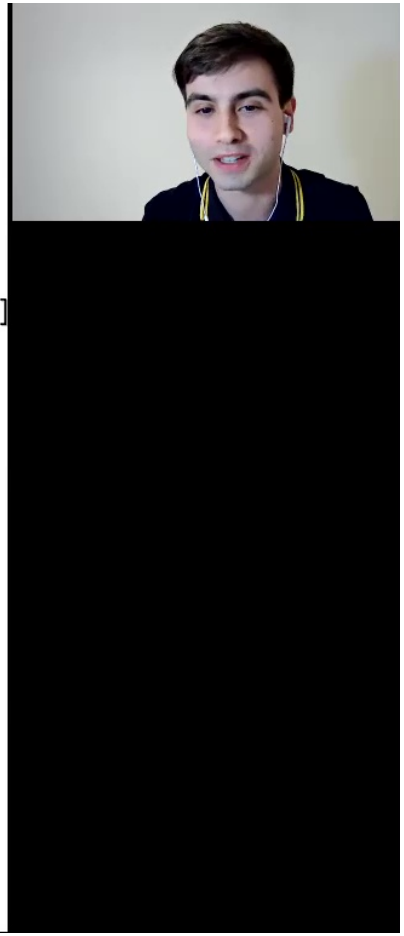
Linear memory

[Zel'Dovich & Polnarev '74; Braginsky & Grishchuk '85; Braginsky & Thorne '87]

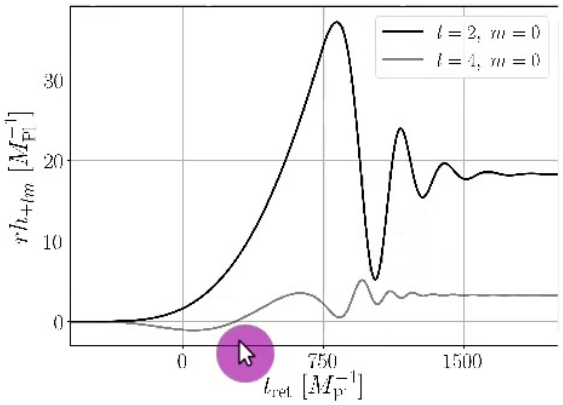
Non-linear memory

[Christodoulou '91. Thorne '92]

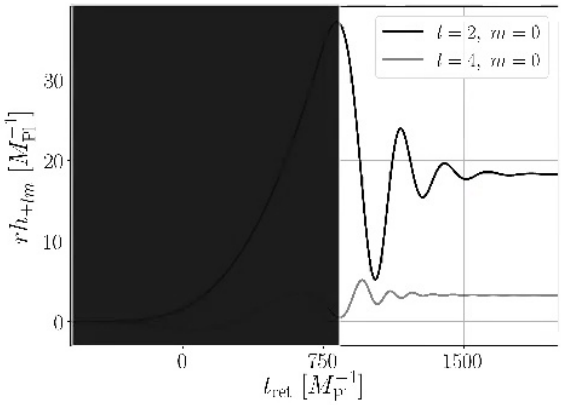
$$\Delta h \propto \left[E_{\rm rad}\left(\frac{v_i v_j}{1-v cos\theta}\right)^{\rm TT}\right]_{\rm out} - \left[E_{\rm rad}\left(\frac{v_i v_j}{1-v cos\theta}\right)^{\rm TT}\right]_{\rm in}$$

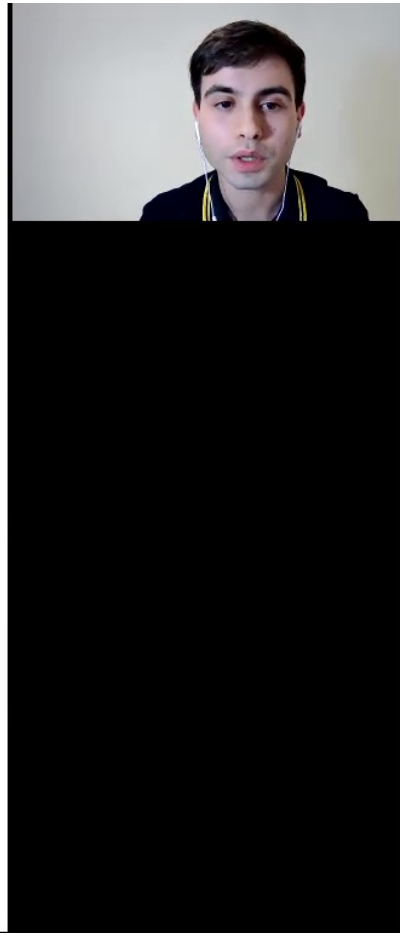


Ongoing and future work

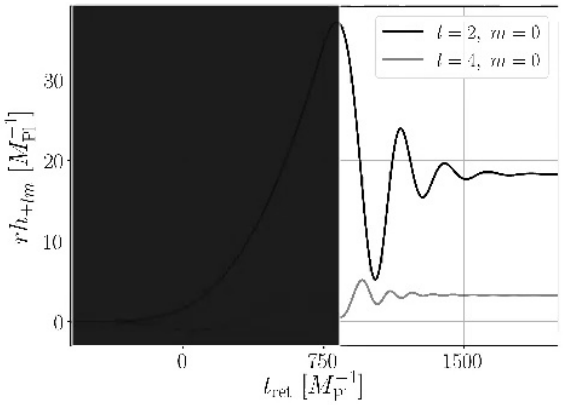


Ongoing and future work





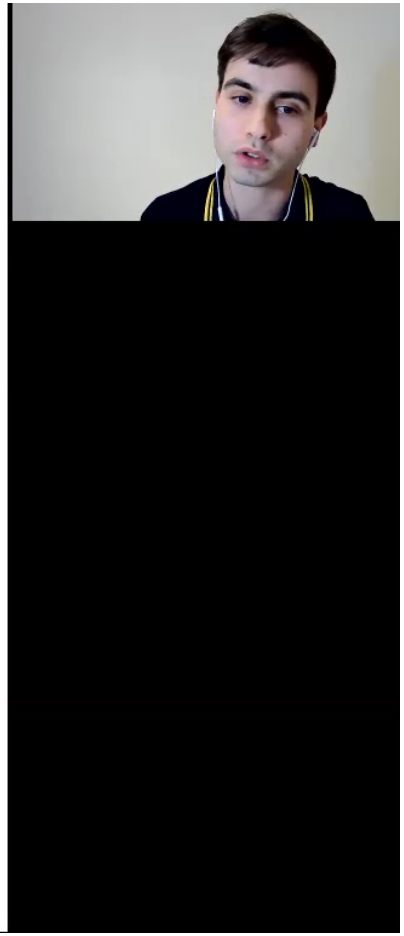
Ongoing and future work



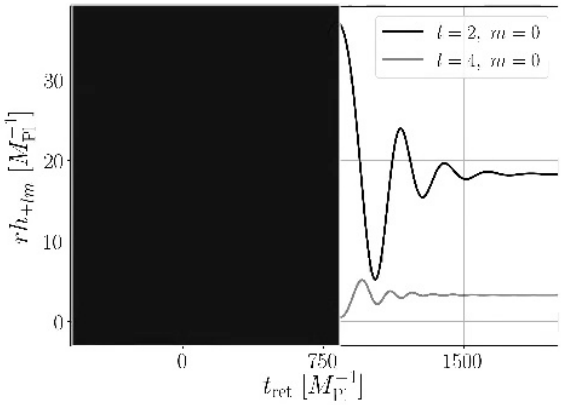
Very massive BBHs ≠ atypical GW progenitors?

Mode content

Williamson, JA, Helfer, Lim, Nissanke (21XX)



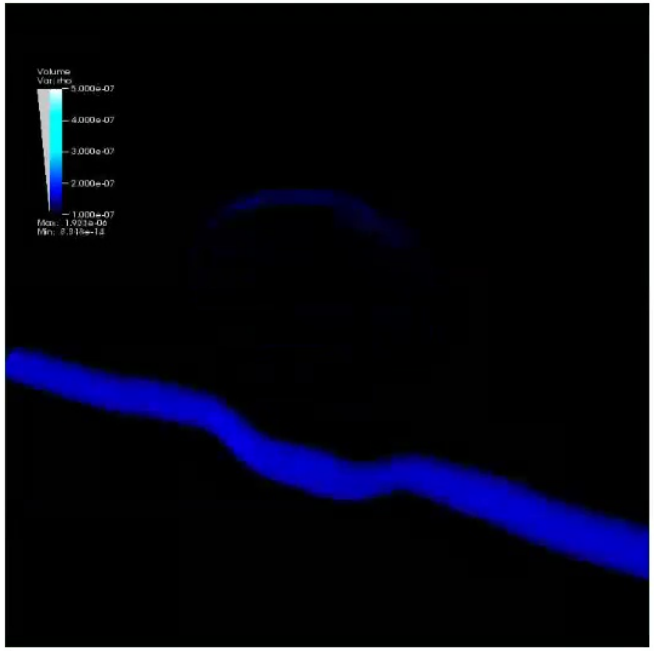
Ongoing and future work

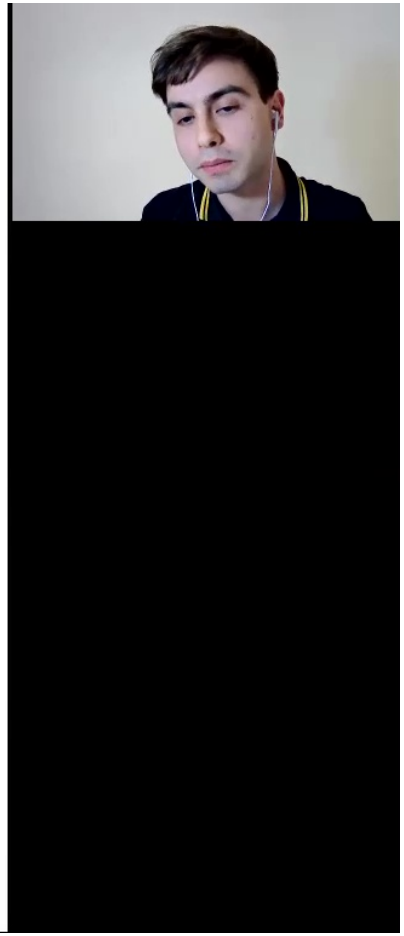


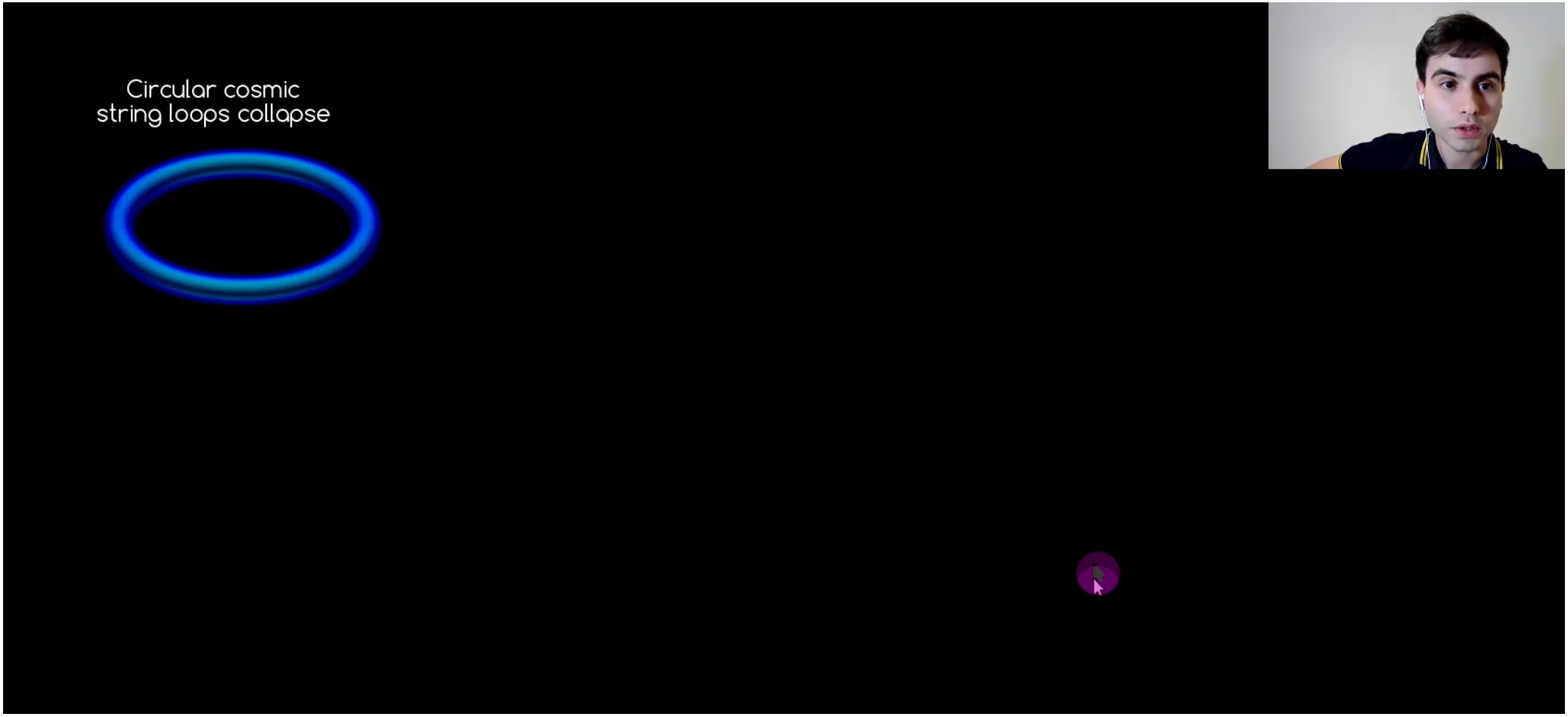
Very massive BBHs ≠ atypical GW progenitors?

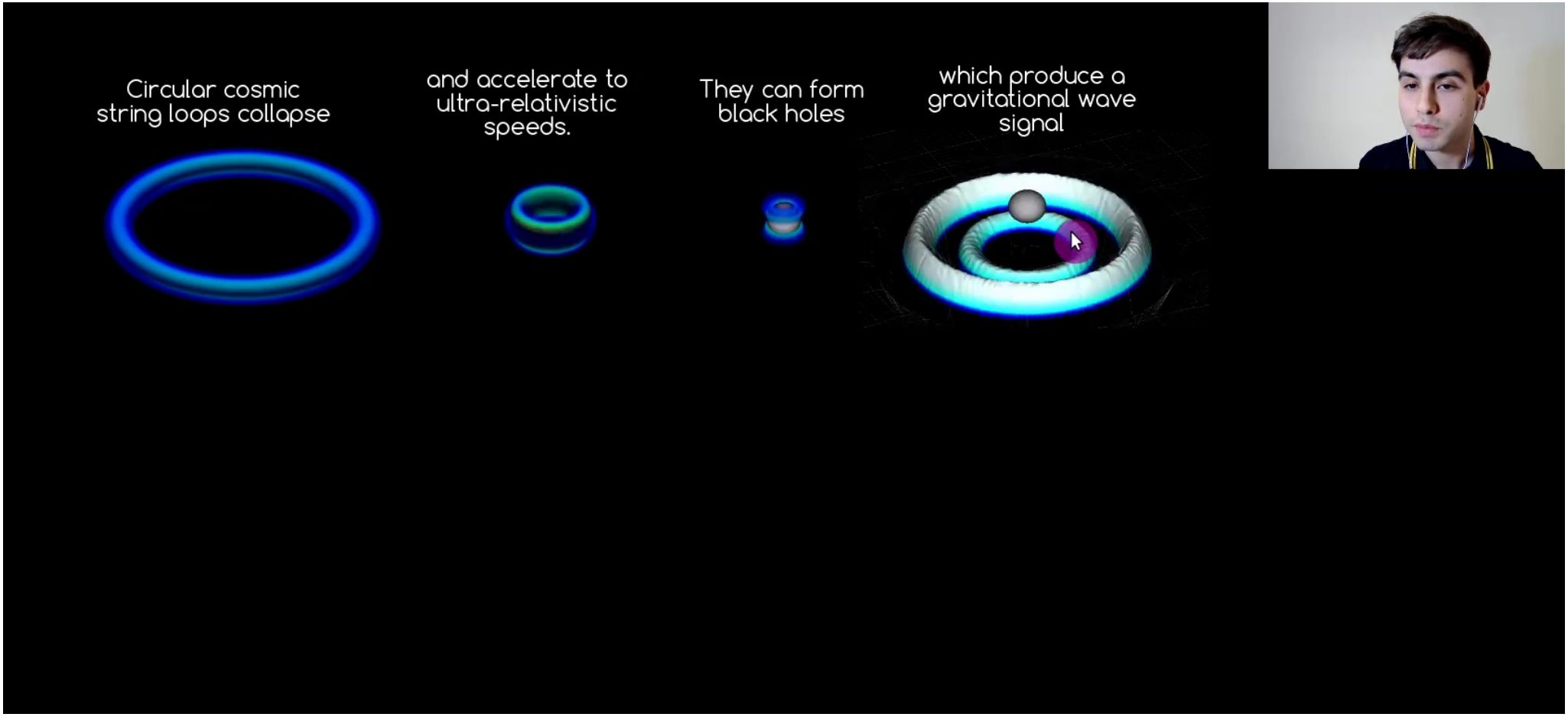
Mode content

Williamson, JA, Helfer, Lim, Nissanke (21XX)






Circular cosmic
string loops collapse


Circular cosmic string loops collapse
and accelerate to ultra-relativistic speeds.
They can form black holes
which produce a gravitational wave signal

Circular cosmic string loops collapse

and accelerate to ultra-relativistic speeds.

They can form black holes

which produce a gravitational wave signal

Thank you